Modeling the High Plains Aquifer's Response to Land Use and Climate Change

By
Reuben Dietrich Dermyer

Submitted to the graduate degree program in Civil, Environmental, and Architectural Engineering and the Graduate Faculty of the University of Kansas in partial fulfillment of the requirements for the degree of Master of Science.

Chairperson Belinda Sturm

Bryan Young

Johannes Feddema

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The Thesis Committee for Reuben Dermyer
certifies that this is the approved version of the following thesis:

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Chairperson Belinda Sturm

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Abstract:

The High Plains Aquifer is extremely important to the economic life of Kansas and the surrounding states, but water is being withdrawn from the aquifer much faster than it is being recharged. Due to the importance of irrigated agriculture to the multi-state region, the imbalance in water-use threatens long-term economic stability. In order for water resource engineers to plan for responsible and sustainable-use of the aquifer, they must be able to predict future water demand with predicted changes in climate and land-use. Seven target counties overlying the High Plains Aquifer were chosen to develop a method of predicting water-use based on land-use and weather records. A water budget model was created to predict irrigation withdrawals from the High Plains Aquifer based on crop-specific evapotranspiration, and the model was validated based on historic reported water-use, weather data, and land-use. In the seven target counties, predicted water use matched historic reported water use with a slope of 1.015. This new model could be used to predict future irrigation demand under different land-use and climate conditions. Additionally, the link between withdrawals and groundwater levels was examined for the seven target counties. In some counties, the change in water surface elevation was correlated with water-use, but in others, the amount of water withdrawn from the aquifer had no impact on the water table. In order to model the impact of future irrigation demand on the aquifer, physical groundwater models such as SWAT and MODFLOW should be utilized.

Acknowledgements:

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List of Abbreviations

AE – Actual evapotranspiration. Units: mm/d
C_d – Constant in the Penman-Monteith evapotranspiration model that changes depending on reference crop and time step.
C_n – Constant in the Penman-Monteith evapotranspiration model that changes depending on reference crop and time step.
e_a – Actual vapor pressure. Units: kPa
e_s – Saturation vapor pressure. Units: kPa
ET – Evapotranspiration. Units: mm/d
ET_c – Evapotranspiration for a specific crop. Units: mm/d
ET_{sz} – Standardized reference crop evapotranspiration. Can also be ET_{os} or ET_{rs} to be grass- or alfalfa-reference ET, respectively. Units: mm/d
G – Soil heat flux. Assumed to be zero for daily timesteps. Units: MJ/m^2
J – Number of the day of the year. 1 for January 1, 152 for June 1 (non leap year)
K_c – Crop coefficient for use with reference evapotranspiration
R_a – Extraterrestrial solar radiation. This is dependent on time of year and location and can be calculated without the need for measurements. Units: $MJ/m^2/d$
R_n – Net radiation at the crop surface. Units: $MJ/m^2/d$
R_{nl} – Net incoming shortwave radiation. Units: $MJ/m^2/d$
R_{ns} – Net outgoing longwave radiation. Units: $MJ/m^2/d$
R_s – Incoming solar radiation. Units: $MJ/m^2/d$
R_{so} – "Clear sky" solar radiation.
T – Mean daily temperature. Can also be T_{max} and T_{min} for the daily maximum and minimum temperature, respectively. Units: °C
u_2 – Wind speed at 2 meters above the ground surface. Units: m/s
WHC – Water holding capacity. Units: mm
z – Elevation of the site. Units: meters
γ – Psychrometric constant. This constant is related to the specific heat of moist air, the latent heat of vaporization, and atmospheric pressure. Atmospheric pressure is being calculated strictly from elevation, so this value will be constant for each location with respect to time. Units: kPa/°C
Δ – Slope of the saturation vapor pressure curve
δ – Solar declination angle. Units: radians
σ – Stefan Boltzmann constant. Value: $4.901 * 10^9$ $MJ/°K^4/m^2/d$
ϕ – Latitude of site. Units: radians
ω_s – Sunset hour angle. Units: radians

The High Plains Aquifer

The High Plains Aquifer covers approximately 174,000 square miles and is overlain by parts of eight different states: Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming [1-2]. The aquifer is one of the most important regional economic drivers due to the importance of irrigated agriculture in the region [3]. Over 95% of the land area overlying the aquifer is devoted to either agriculture or rangeland [4]; this land produces between 15 and 20 percent of all corn, cotton, wheat, and cattle in the nation [1].

Water levels in the High Plains Aquifer began to see declines around 1950, when groundwater irrigation became widespread throughout the region. The water surface elevation before significant groundwater irrigation began is usually termed "predevelopment" [5-6]. The entire aquifer system, as well as the change in water surface elevation from predevelopment through 2007, can be seen in Figure 1. Much of the aquifer has experienced severe declines in the water table, with parts of Kansas and Texas being the hardest hit. The southwest corner of Kansas has experienced the most significant loss of water in the state – much of the region has experienced a drop in water level of over one hundred feet. Multiple regional aquifers make up the much larger High Plains Aquifer – the most well-known of which is the Ogallala Aquifer, which commonly lends its name to the system as a whole. In Kansas, the principal aquifers are the Ogallala, the Great Bend Prairie, and the Equus Beds aquifers [7]. This aquifer system occupies approximately 30,500 square miles of Kansas [2, 7], all in the central and western portions of the state (as seen in Figure 2).

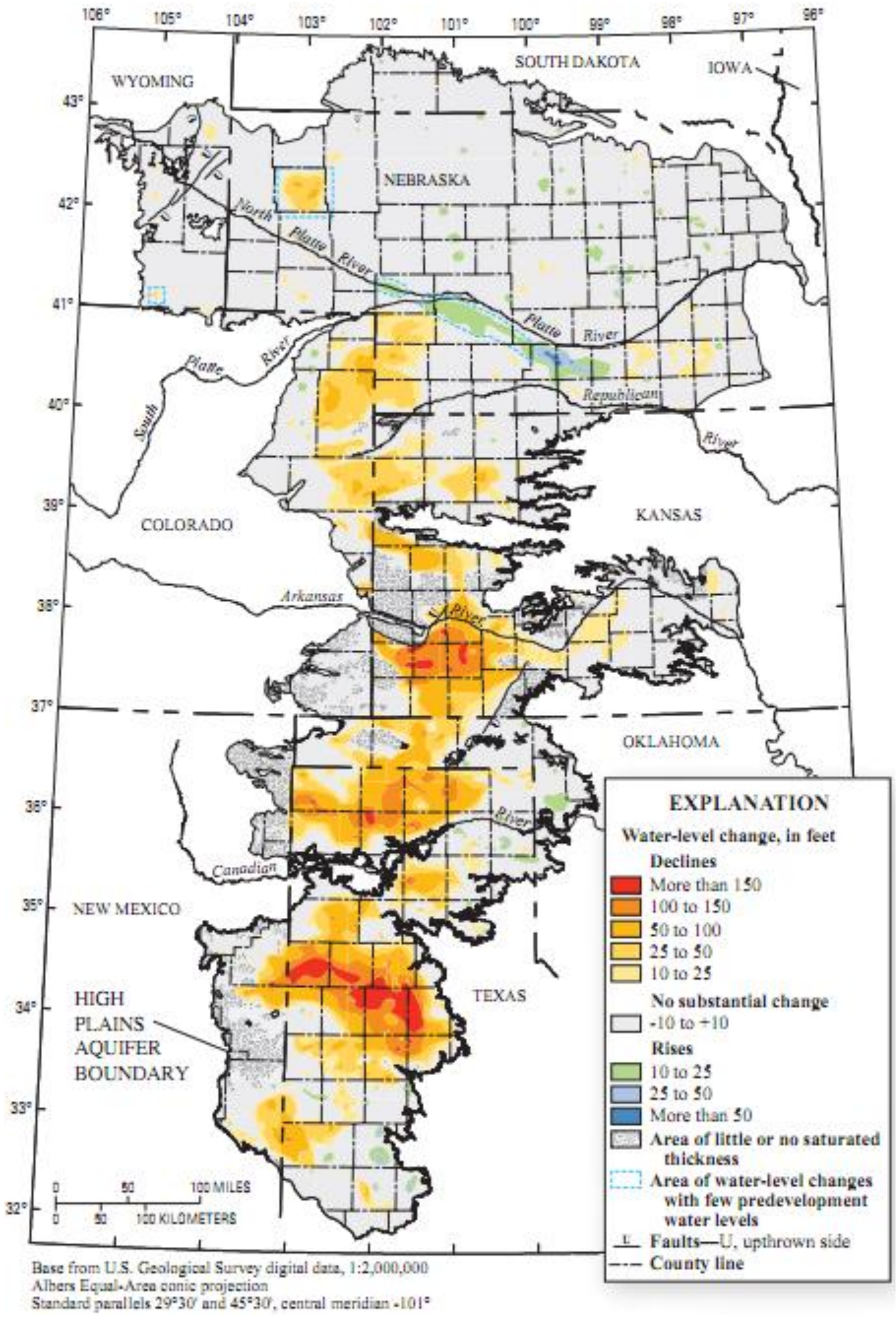

Figure 1: Map of the High Plains Aquifer, showing the change in water level from Predevelopment to 2007 [7]

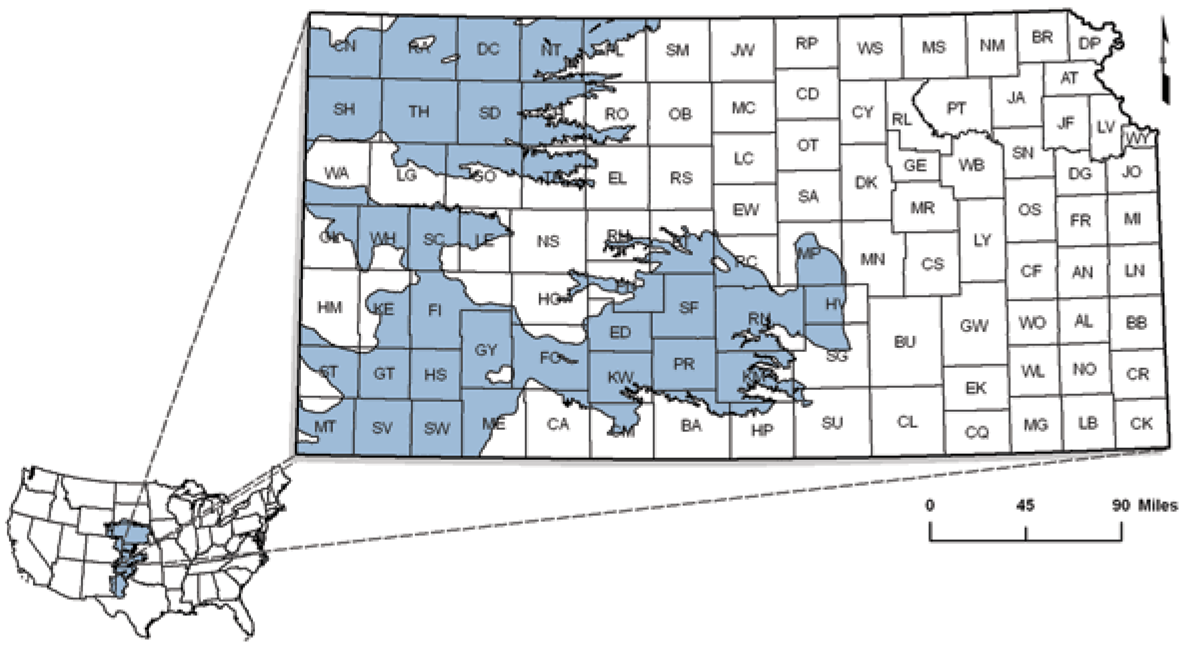

Figure 2: The High Plains Aquifer in Kansas [7]

The High Plains Aquifer is the single most important source for fresh water in the state – approximately 70% of the water used in Kansas comes from this aquifer [7]. In counties overlaying the High Plains Aquifer, nearly all water is supplied from a groundwater source (Figure 3). Additionally, these counties tend to use much more water for irrigation than other counties (Figure 4), although this is also affected by the decrease in precipitation from east to west across the state (only 16-18 inches on the Colorado border, but over 38 inches annually on the Missouri border [8]).

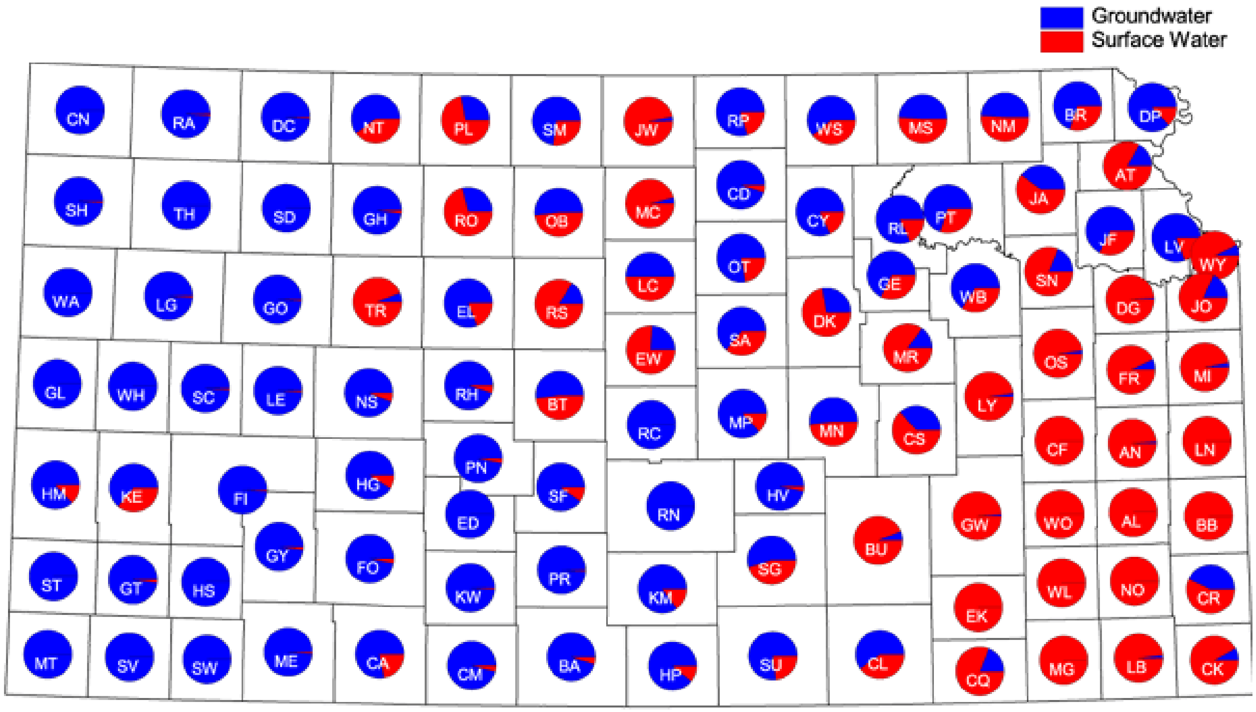

Figure 3: Percentage of water from ground or surface water sources by county in 2000 [9]

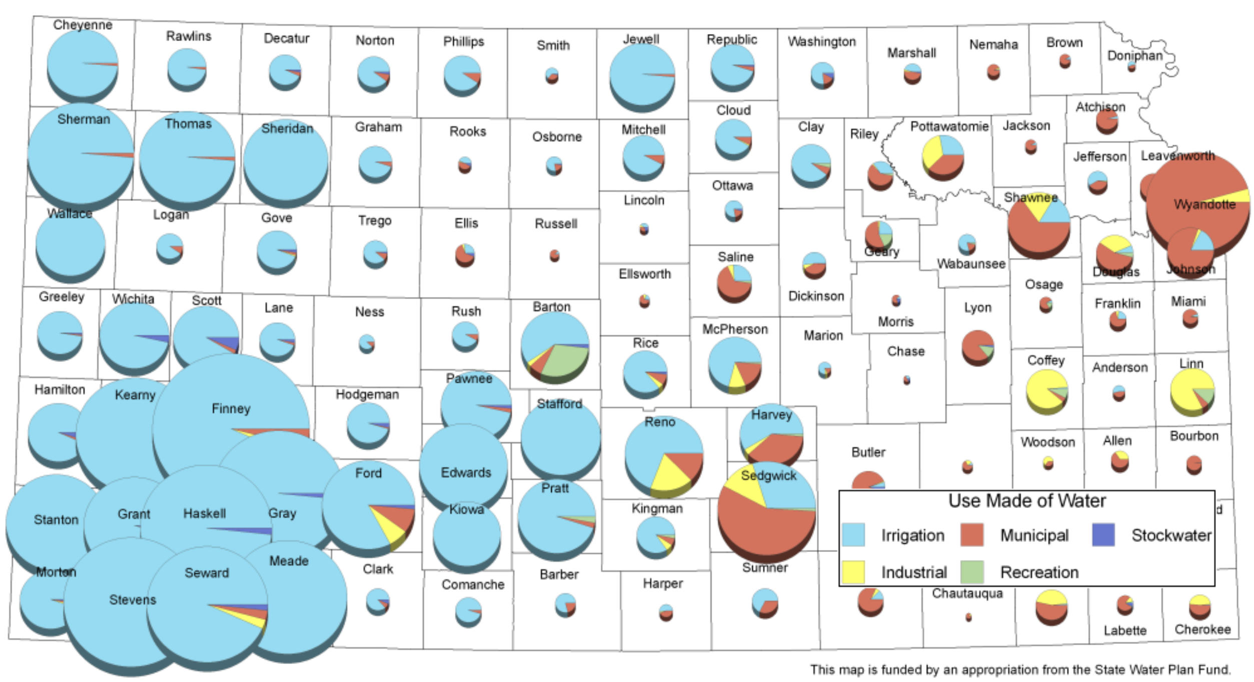

Figure 4: Percentage of water going to each use by county in 2007; larger circles indicate a larger quantity of water used [10]

With the exception of central Kansas, where sandy soils, higher rates of precipitation, and a high water table contribute to recharge of up to 4-6 inches per year, the High Plains aquifer is primarily limited to an inch or less of recharge each year [2, 7, 11-12]. This slow rate of recharge and the importance of irrigated agriculture to the economic life of the region lead to a drastic imbalance in water sustainability and economic stability in Kansas. In a typical year, 1.5 million acre-feet are recharged to the aquifer, but 4.4 million acre-feet were withdrawn in 2007 [7]. The imbalance between withdrawals and natural recharge has resulted in groundwater becoming a non-renewable resource that will run out without effective management. The effect on the aquifer is by no means uniform. Based on a KGS study, discussed later, parts of southwest Kansas still contain enough water that irrigation can continue at current rates for another 50 to 200 years, but most of Greeley, Lane, Scott, and Wichita counties are either depleted or have less than 25 years of water left. [7].

Any decrease in the water surface elevation makes irrigation more expensive. A smaller saturated thickness leads to a decrease in pumping capacity [13], and a lowering of the water table leads to an increase of pump head, which increases the energy required to lift a given amount of water and could affect pumping rate or pump efficiency. A drop in the water table of only one foot increases the amount of energy it takes to lift one acre-foot of water by 1.7 kilowatt-hours [14].

Overview of studies on the High Plains Aquifer

The High Plains Water-Level Monitoring Study (HPWLMS) is a program through the United States Geological Survey to provide biannual reports on the changes in the High Plains Aquifer throughout the eight states that overlie the aquifer. The goals of the HPWLMS are to collect and assimilate water level measurements from state, local, and federal agencies, map changes in the water surface elevation, and to estimate the change in water in storage in the aquifer [15]. Each year, approximately 9,000 measurements are collected, with more than 1,000 coming from Kansas [6]. The measurements from Kansas primarily come from the Kansas Geological Survey and the Department of Water Resources [16-17] and are concurrently stored in the Water Information Storage and Retrieval System, or WIZARD.

The USGS calculates the area-weighted change in water surface elevation using either Thiessen polygons (for measurements after 1988) or a 500 square meter grid (for change in water level since predevelopment) [5-6]. Only wells that had measurements in both the starting and ending year are used: for example, the change in water surface elevation from 2005 to 2007 was calculated by using only the wells that were measured in both 2005 and 2007. The change in water surface elevation at each well site was converted to a change in volume by multiplying by either the grid size or the area of the Thiessen polygon and by the area-weighted specific yield of 0.15 [5-6]. Data from each report from 2002 through 2007 were compiled to create Figure 5, which shows the state-wide average changes in water surface elevation and storage in the High Plains Aquifer from 2002-2007 [5-6, 18-20].

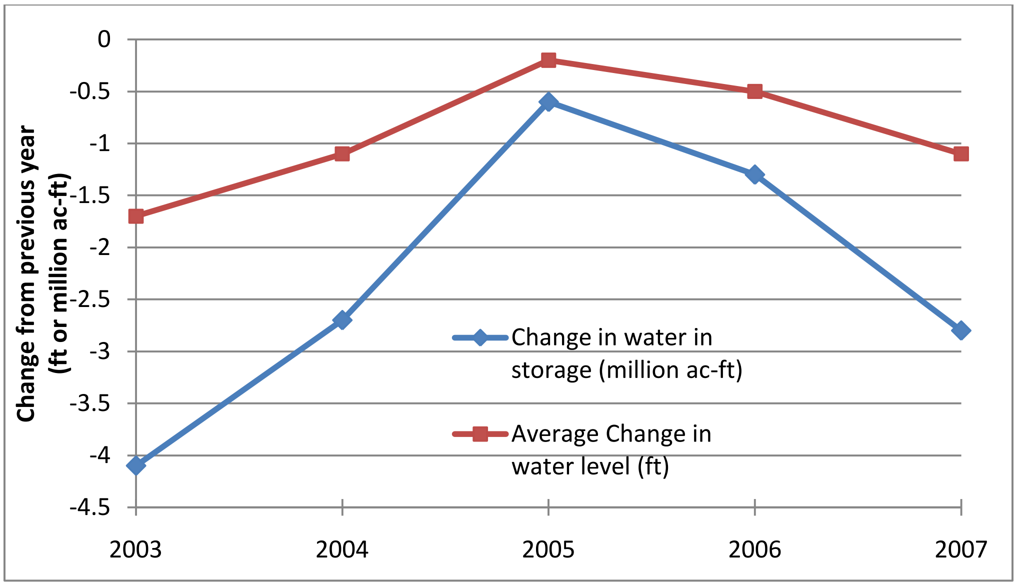

Figure 5: Annual change in storage and water level for Kansas from 2002 through 2007. Compiled from [5-6, 18-20]

Estimates of remaining usable lifetime of the High Plains Aquifer have been performed by the USGS and KGS, among others. These studies primarily project past rates of decline in the water surface elevation forward to predict when the saturated thickness falls below a certain level [7, 21-23]. A thickness of 30 feet is normally chosen as the limiting thickness for irrigation pumping [7, 21-23]. At this saturated thickness, the intense pumping necessary for irrigation becomes impractical due to the large cones of depression caused by high-volume pumping [22, 24], but it still allows for most domestic, municipal, and infrastructure groundwater needs to be met. Advanced practices could potentially allow for irrigation pumping below this level, which could deplete the aquifer to such a level that would not allow these basic needs to be met [25]. A recent estimate of the usable life of the High Plains Aquifer by the KGS in Kansas is shown in Figure 6. This study took the average annual rate of change from 1998-2008 and assumed that it would remain constant over time. Projecting this rate into the future allowed the KGS to estimate how many years it would take for the aquifer to reach the minimum saturated thickness of 30 feet. Many areas of the state are already below this minimum threshold and others are within 25 years of this limitation [7].

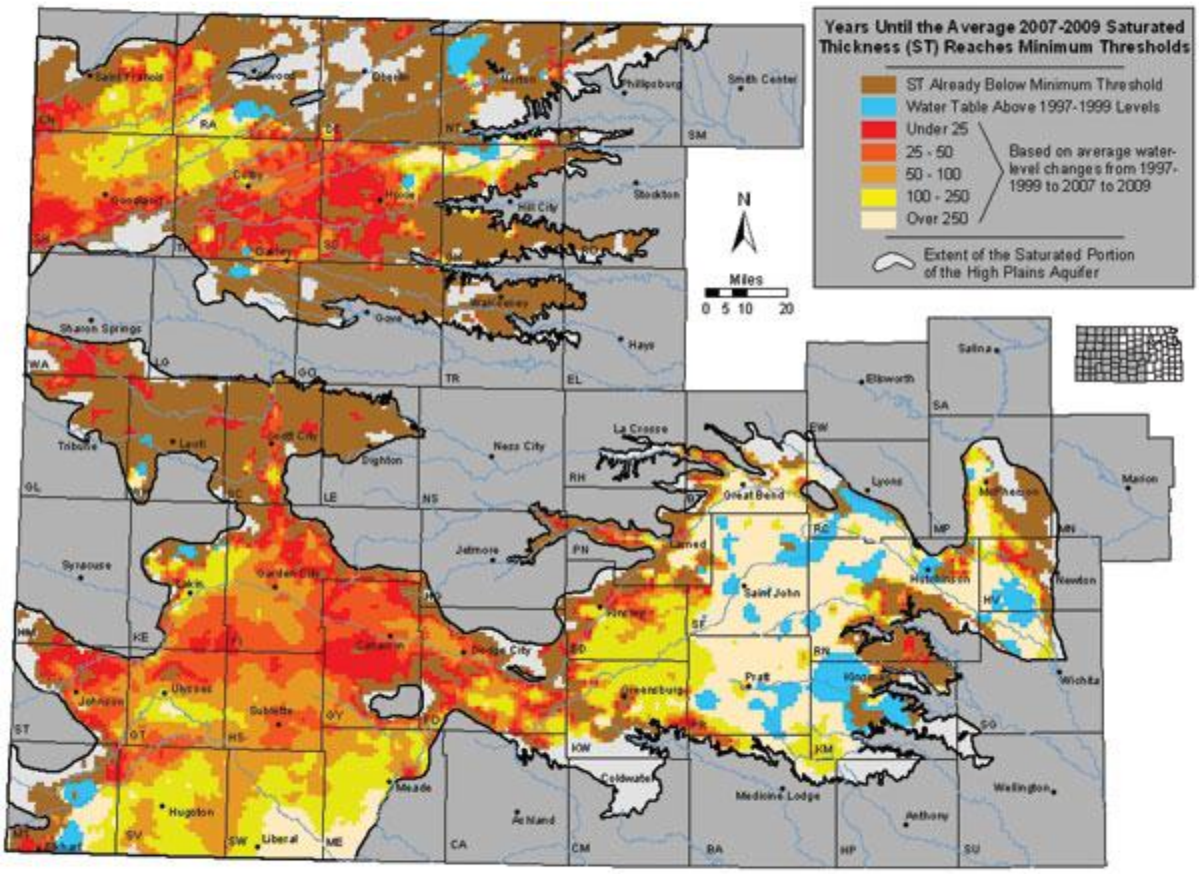

Figure 6: Estimated life of the aquifer from 2008, based on annual change in water surface elevation from 1998-2008 [7]

A different study to estimate the usable life of the aquifer used different values for the minimum saturated thickness, replacing 30 feet with minimums based on pump yields (of 50, 400, and 1,000 gpm) and aquifer characteristics [21]. In that study, the change in water level was still based on average annual rates of decline. This study also investigated the relationship between water use and groundwater levels. Yearly water levels and water use density (in acre-feet withdrawn per square mile) were plotted on a 500 meter grid [16, 21]. This allowed for regionalizing the water use instead of being limited to water use at discrete points. Southwest (GMD 3) and west-central (GMD 1) Kansas both exhibited a good relationship between groundwater levels and groundwater use per square mile, while northwest Kansas (GMD 4) has a weaker correlation [21]. Any predictions for usable life in this study relied purely on the average annual change in water surface elevation.

Groundwater models in the High Plains Aquifer tend to be at the watershed scale and often utilize both SWAT (Soil and Water Assessment Tool) and MODFLOW (Modular Three-Dimensional Groundwater Flow Model) to determine the interaction between surface and groundwater [26]. Basin-scale models have been created for the Rattlesnake Creek watershed in south-central Kansas [26-27], the Republican River in north-central Kansas [26], and Wet Walnut Creek, the location of the Walnut Creek IGUCA [26]. These integrated surface and groundwater models predicted variations in the water table much better than the groundwater model alone [26].

Use of a Water Budget Model

While a physical groundwater model may be the best tool for predicting drawdown of the water table and how that drawdown would affect surface water, the primary purpose of this initial part of the study is to predict irrigation withdrawals from the High Plains Aquifer based on major irrigated crops in Kansas. Combined SWAT-MODFLOW models have been useful in simulating the changes in the parts of the aquifer [26-27], but accurate estimates of future groundwater demand are necessary in order for a groundwater model to produce accurate predictions. After a method for predicting withdrawals is developed, then the impact to the High Plains Aquifer can be estimated for a variety of land-use and climate change scenarios.

A water budget model was chosen because it allows the tracking of water in the soil column throughout the year [28]. Water budgets are commonly used to determine irrigation need based on evapotranspiration [29]. Like an accounting ledger, daily inputs and outputs from the system are tabulated, but precipitation, irrigation, evapotranspiration and water storage in the soil are tracked, instead of credits and debits to a bank account. The idea behind the water budget is that the inputs of water to a system (precipitation and irrigation) minus the outputs of water from a system (evapotranspiration and runoff) equal the change in water stored in the soil:

$$\Delta ST = P + I - ET - R$$

Water budgets operate at a specific temporal scale. For a combined SWAT-MODFLOW model, the timestep is usually monthly due to the infrequency of groundwater measurements and the slow rate at which changes occur [26], but any timestep can theoretically be used. Runoff and infiltration are highly dependent on soil moisture conditions, so a daily timestep is recommended for modeling the hydrologic processes the water budget depends on [26]. Additionally, evapotranspiration calculations are more accurate on a daily scale than on a monthly scale [30]. The water budget developed to estimate irrigation demand operates on a daily timestep due to the availability of weather data and the highly variable nature of Kansas weather.

Purpose of Project and Approach

Due to the unsustainable use of the High Plains Aquifer and its economic importance to the region and the country as a whole, an understanding of the interconnectedness between climate, land-use, and groundwater will be invaluable in aiding the responsible stewardship of natural resources.

Because irrigation is the largest portion of groundwater withdrawals from the High Plains Aquifer, the ability to predict irrigation demand would enable a better estimate of the future impact to groundwater levels based on varying climate or land-use scenarios. Annual water-use and water levels were analyzed to identify common trends, and a water budget model was created to estimate irrigation demand based on actual crop evapotranspiration. This model was validated using historical crop acreages, water use, and climate data.

This model will provide a valuable tool to predict irrigation demand at the county level, but predictions will depend on many factors. Intergovernmental Panel on Climate Change (IPCC) projections can inform the evapotranspiration calculations, but the amount of cropland dedicated to irrigated agriculture is dependent on many factors. This decision to irrigate is complicated and both influences and is influenced by the accessibility of groundwater – depression of the water table due to irrigation may make irrigation less feasible due to increasing costs. Concerns about runoff of fertilizers and pesticides affecting water quality may weigh on a farmer's mind as decides what crops to plant, how and where to plant them, and if and how much he irrigates. The feedback between the many factors is illustrated in Figure 7.

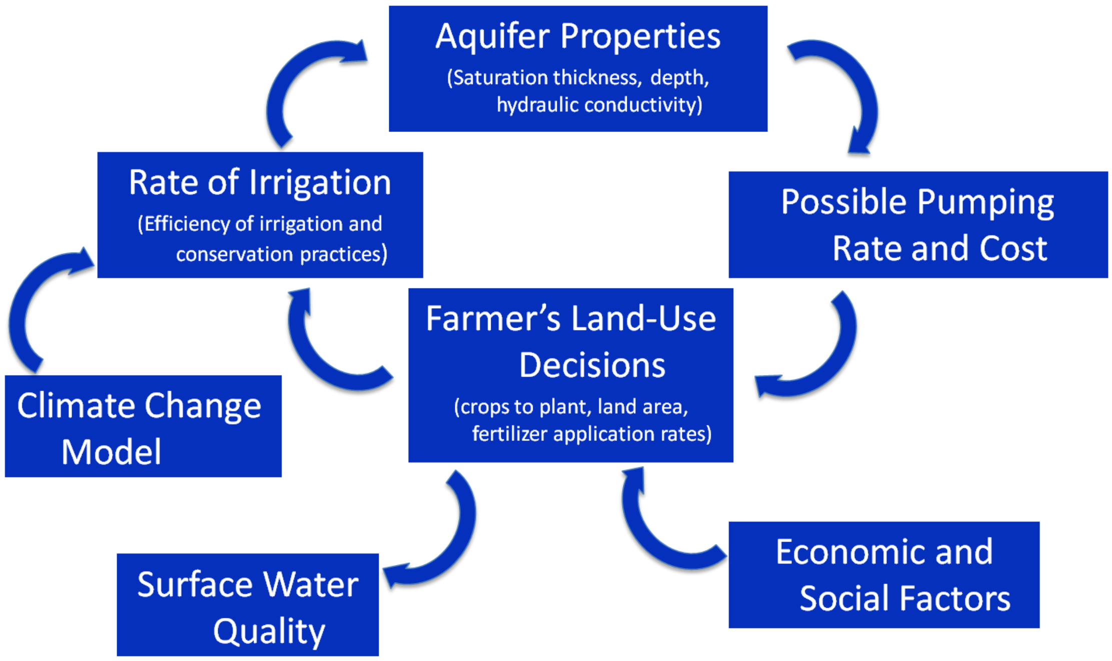

Figure 7: The model feedback loop

Selection of Target Counties

There are five specially designated Groundwater Management Districts (GMDs) spread throughout central and western Kansas. Each GMD contains between 4 and 12 counties and oversees regional groundwater policy and assists landowners with conservation measures such as the installation of flow meters, conversion to dryland farming, and retirement of water rights.

This analysis will look at 7 counties. The target counties are Barton, Finney, Morton, Reno, Stafford, Stevens, and Thomas. These counties were chosen for their wide range of water demand, good geographic distribution across the High Plains Aquifer, and proximity to weather stations. Additionally, Barton County, in GMD 5, contains the McPherson Intensive Groundwater Use Control Area (IGUCA) and is impacted by the Walnut Creek IGUCA. The Kansas Department of Water Resources sets up IGUCAs if conditions warrant an adjustment to how water rights are managed or awarded [31]. Because Kansas follows the doctrine of "first in time, first in right," IGUCAs are necessary in critical areas to preserve water quality or quantity. The McPherson IGUCA was the first in the state, set up on February 13, 1979 due to excessive groundwater decline and comparatively negligible recharge [31-32]. The Walnut Creek IGUCA was established in 1990 and is the only IGUCA where active water rights were reduced [31, 33-34]. The Groundwater Management Districts and target counties are highlighted in Figure 8.

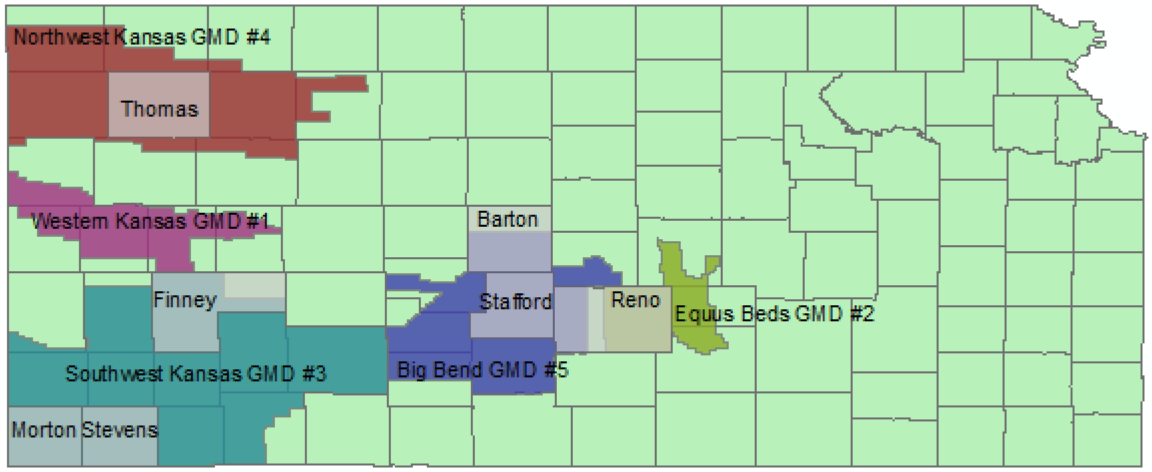

Figure 8: Selected counties and Groundwater Management Districts in Kansas

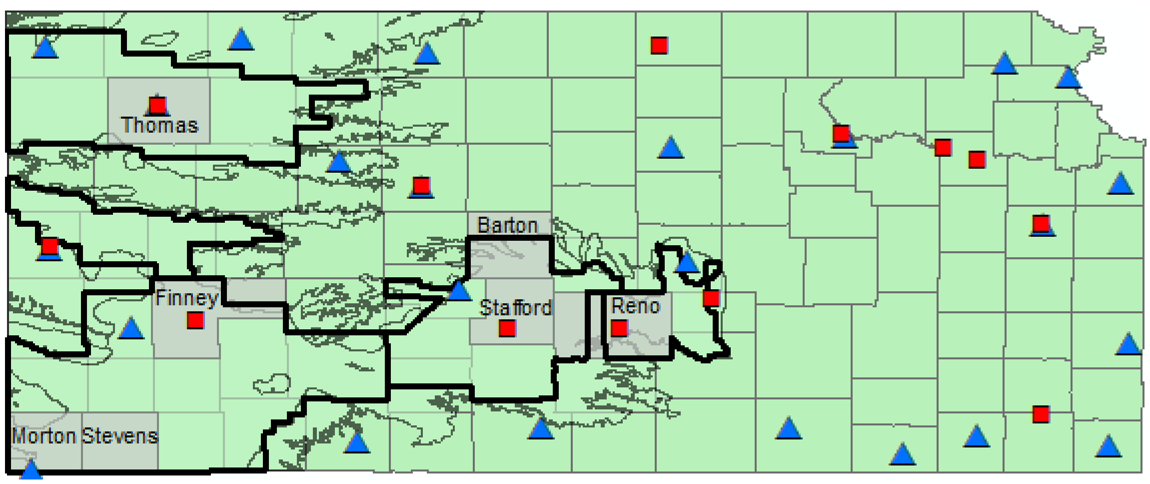

Figure 9: Locations of weather stations superimposed over the High Plains Aquifer. The red squares are the HPRCC weather stations, and the blue triangles are the long term weather stations.

The county selection also took into account the location of weather stations in Kansas. Figure 9 shows the locations of the various weather stations in Kansas that have had QAQC performed; this figure omits coop stations. The red squares are the HPRCC automated weather stations (providing air temperature, precipitation, relative humidity, soil temperature, solar radiation, and wind speed) and the blue triangles are the long term weather stations. The long term weather stations provide only temperature and precipitation, but their records have a much longer range – some go back to 1900. Figure 9 also shows the High Plains Aquifer and has the 5 GMDs outlined.

Data Sources

WIMAS

Location: http://hercules.kgs.ku.edu/geohydro/wimas/query_setup.cfm

The Water Information Management and Analysis System (WIMAS) can query any water right in the state of Kansas [35] . The search can be refined by county, source (ground or surface), the end use of the water (irrigation, industrial, etc), or specific water rights can be searched for. For each water right, the total amount of water used is reported by the owner of the water right to DWR. Figure 10 displays all irrigation points of diversion that are from a surface water source – very few overlie the High Plains Aquifer.

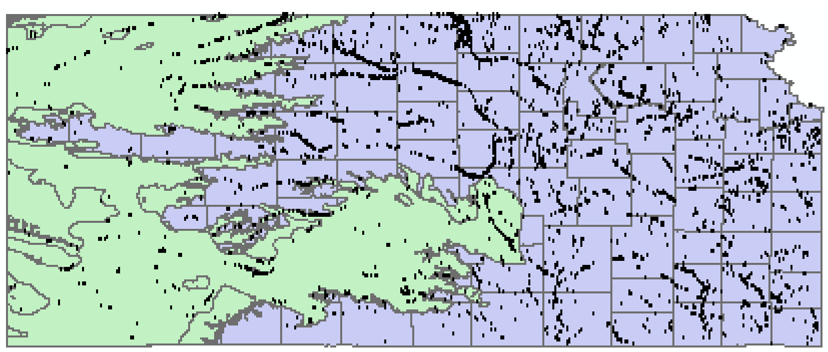

Figure 10: Locations of irrigation by surface water

An open records request to the Kansas Department of Water Resources was processed December 2010 for data from 1985 through 2009. A Microsoft Access database was provided including water rights information for all counties in the state. A metadata file is provided in Appendix A. The annual withdrawals for every water right in the state, irrespective of source and end use, were included in this database.

Additionally, WIMAS provides the legally binding limitation on water use by water right. This limitation is valid on the day that the data are retrieved; WIMAS does not make allowable usage for previous years easily accessible. The total legally available water for each target county was determined by summing the authorized quantities that were available in each year, assuming that the present-day limitation for each well was valid throughout its life. The total authorized withdrawals for Stafford, Stevens, and Thomas Counties from 1985 through 2009 are shown in Figure 11. The actual amount used in any given year generally stays within 40 to 70% of the authorized quantity

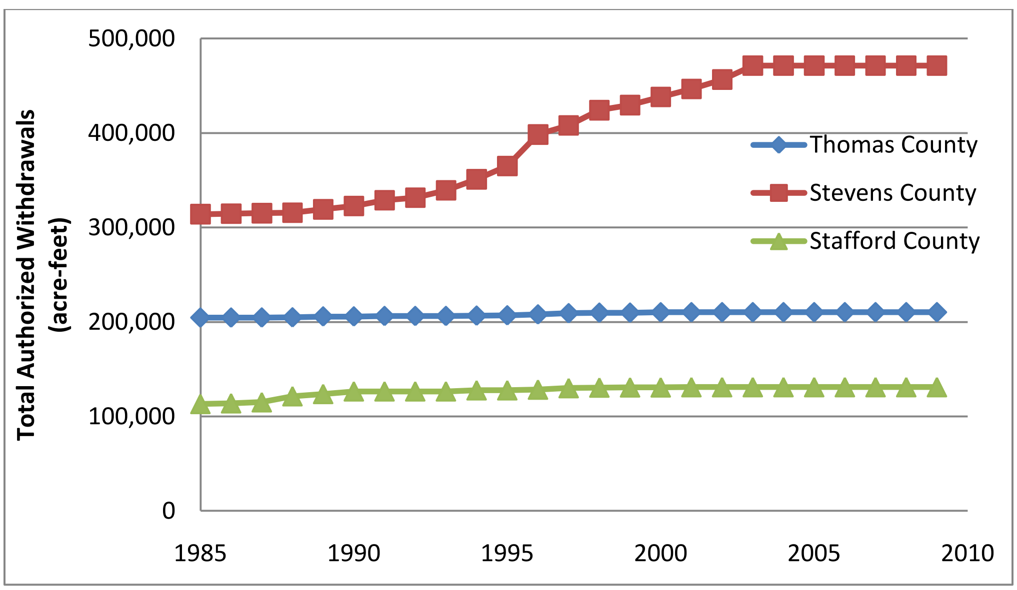

Figure 11: Authorized withdrawals from WIMAS for Stafford, Stevens, and Thomas Counties, 1985-2009

WIZARD

Location: http://www.kgs.ku.edu/Magellan/WaterLevels/index.html

The Water Information Storage and Retrieval Database (WISARD/WIZARD) houses historical well measurements [36]. Each measurement of depth to water is linked to a specific well that is geocoded with latitude and longitude. As can be seen from Figure 12, wells are primarily located above the High Plains Aquifer and clustered along the rivers.

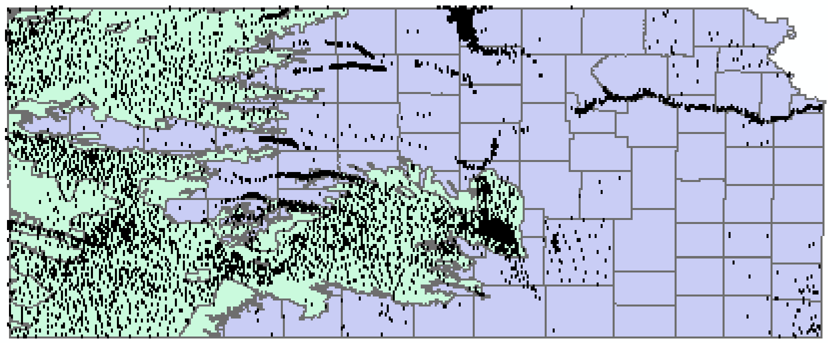

Figure 12: Locations of WIZARD well measurements

Yearly water levels were downloaded for all wells. Additionally, an average depth to water at each well for each water year was calculated. Only winter measurements were used (December through February); if a well had multiple measurements in these months, then an average value was used. The measured water surface elevation is assigned to the year of January/February, so if a well was measured in December 2005 and again in February 2006, the two measurements would be averaged for that well's 2006 measurement.

This dataset was retrieved on 12 December 2010 by Matt Hiatt.

WWC5

Location: http://www.kgs.ku.edu/Magellan/WaterWell/index.html

Whenever a new well is drilled, the driller fills out a drilling log. This log primarily contains information about the location, owner, and driller of the well, but it may also contain geologic information, such as where different soil layers occur in the soil column and the depth at which the drill encountered groundwater. The Kansas Department of Health and Environment stores all of the submitted logs in the Water Well Completion Form Database, or WWC5.

Because the WIZARD measurements are primarily focused on the High Plains Aquifer, a supplemental data source is necessary. Figure 13 shows a section of southeast Kansas – the WIZARD measurements, represented by the brown dots, are completely absent in some counties while WWC5, represented in green, contains measurements for every county. The WWC5 database is needed to fill in these large unknown areas that are found away from the High Plains Aquifer and the major rivers in the state. These measurements are performed by the well driller on the date that the well is drilled, so they provide a snapshot of conditions as they were on the day that measurements were taken – a measurement during the summer may be influenced by irrigation withdrawals. Many of the measurements in the WIZARD database are performed by the Kansas Geological Survey or the Division of Water Resources whereas the measurements in WWC5 are taken as a secondary purpose – the well driller is there not to measure where groundwater occurs but to provide access for his clients. Despite the potential differences in quality of the two databases that stems from the difference in measurements, both databases will be equally included due to the need for measurements of any kind in parts of the state.

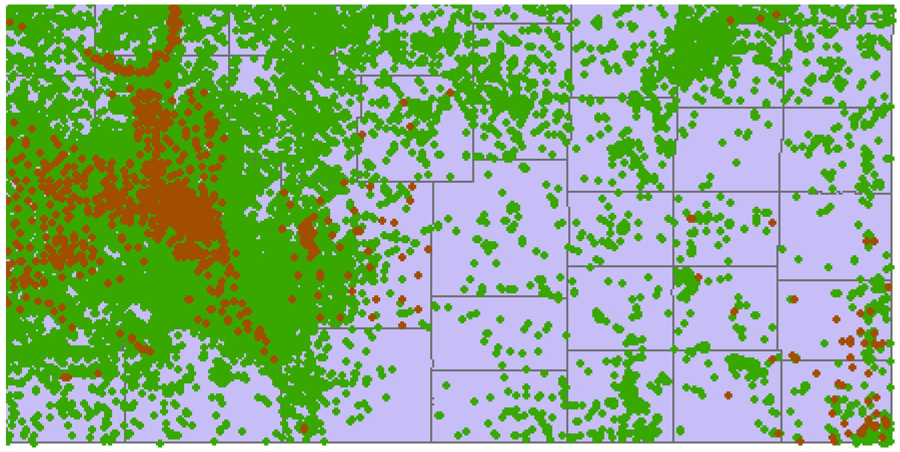

Figure 13: Comparison of the WIZARD (brown) and WWC5 (green) databases in southeast Kansas.

This dataset is missing the land surface altitude at the well, which is required to determine the elevation of the water table, but this can be estimated from the Kansas Data Access and Support Center's digital elevation models (DEMs) for the state of Kansas (located at http://www.kansasgis.org/catalog/index.cfm, then click on "Elevation" and "National Elevation Dataset"). The four supplied raster files where then merged together and the elevation was attached to the WWC5 wells using the "Extract Values to Points" tool in ArcMap (found in "Spatial Analyst" – "Extraction"). This elevation field was then converted from meters to feet to maintain consistent units between data sources. The interpolation of the elevation WWC5 wells adds additional uncertainty to any measurements at these wells.

From the complete dataset (219,295 entries), wells were removed that had no spatial reference, no water levels, or were drilled prior to 1985. This left 137,985 wells in the shapefile "WWC5_Sites". Of the wells that were drilled during this date range, only the measurements that took place between November and March were used, leaving 46,942 measurements from 1985 to 2010 – this selection is shown in Figure 14.

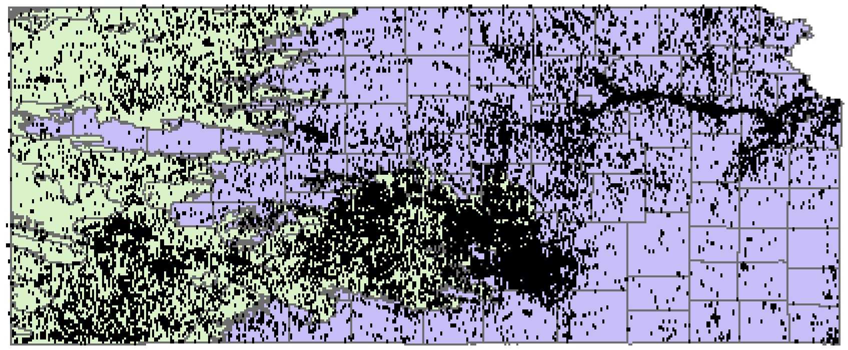

Figure 14: The result of merging the WWC5 and WIZARD databases

USGS

Location: http://water.usgs.gov/lookup/getgislist

This website houses a variety of shapefiles, including shapefiles consisting of the physical properties of the High Plains Aquifer. It includes shapefiles for aquifer base (ofr98-393_aqbase), the aquifer boundary (ofr99-267), hydraulic conductivity (ofr98-548), and specific yield (ofr98-414). These files were obtained in the form of ArcInfo Interchange files (*.e00) and converted to shapefiles using the "Import from Interchange" tool in ArcCatalog.

NASS

Location: http://www.nass.usda.gov/Data_and_Statistics/Quick_Stats/index.asp

Irrigated acreage was retrieved from the National Agricultural Statistics Survey. NASS Quickstats 1.0 [37] was used to retrieve the yearly, county-level irrigated areas by crop. Some years, counties, and crops are missing data, but these values can be interpolated or estimated to provide a reasonable value based on the trends of the surrounding years and the reported Census of Agriculture values (if applicable) [38-41]. These estimated values are marked in the crop area tables, which are found in Appendix B.

Table 1: Irrigated acreage by crop for Thomas County. Comparison of NASS and Ag. Census data 1995-2004. Missing data is shown here as "NA"

	Corn (NASS)	Corn (Ag. Census)	Sorghum (NASS)	Sorghum (Ag. Census)	Soy (NASS)	Soy (Ag. Census)	Wheat (NASS)	Wheat (Ag. Census)
1995	64,800		1,900		3,700		9,700	
1996	65,500		2,900		4,000		7,900	
1997	76,300	70,182	2,100	1,835	6,100	5,215	8,300	5,782
1998	66,200		1,000		7,400		7,500	
1999	72,400		1,400		NA		7,400	
2000	81,500		700		NA		5,600	
2001	74,200		3,800		7,400		8,800	
2002	71,800	59,522	NA	624	NA	11,375	9,200	13,488
2003	62,500		8,100		12,900		15,100	
2004	53,500		3,900		NA		14,500	

As can be seen in Table 1, NASS is missing county level irrigate acreage for several crops over several years. This is not unique to this county or time period; every county is missing at least one crop in one year. Completeness of the dataset is not the only issue, as well. In years where the Census of Agriculture was performed, the tallies from NASS and the Ag. Census rarely match up exactly. In Thomas County in 1997, NASS reported more irrigated acreage for each crop than the Ag. Census, and in 2002 reported 12,000 more acres in irrigated corn but 2,000 fewer acres in irrigated wheat. Data were used from NASS when there was an overlap (1987, 1992, 1997, 2002, and 2007); the Ag. Census was used to aid in the interpretation of irrigated acreage in cases of missing data.

Determining Evapotranspiration Needs

In order to predict future irrigation needs, irrigation demand will be calculated based on crop evapotranspiration. A variety of evapotranspiration methods were tested and evaluated and then compared to historic irrigation water use.

Calculating Reference Evapotranspiration

The High Plains Regional Climate Center (HPRCC) maintains a network of automated weather station encompassing all or part of Colorado, Kansas, Iowa, Minnesota, Missouri, Montana, Nebraska, North Dakota, South Dakota, Wisconsin, and Wyoming. These weather stations record hourly air temperature, relative humidity, soil temperature, wind speed at 2 meters above the land surface, incoming solar radiation, and precipitation. Evapotranspiration is also calculated and reported. Fourteen AWDN (Automated Weather Data Network) stations are located in Kansas (shown in Figure 15), and all provide enough information to perform the reference evapotranspiration calculation using the Penman-Monteith equation.

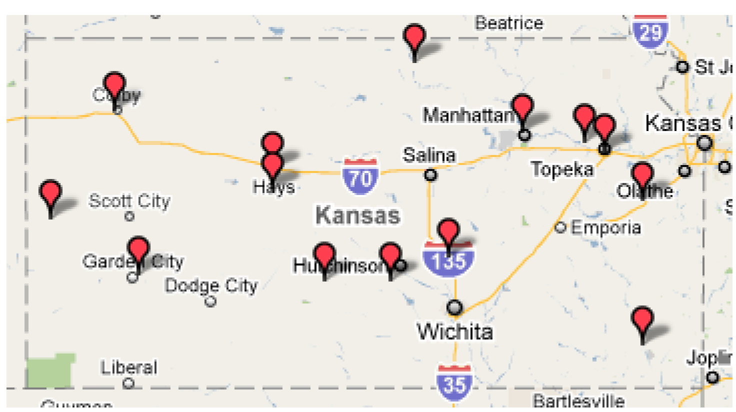

Figure 15: Locations of AWDN Stations in Kansas

Evapotranspiration was calculated for four locations in Kansas (Colby, Garden City, Hays, and Manhattan) for the years 1988-2009 using a variety of methods including the Penman-Monteith [30, 42-45], Hargreaves-Samani [30, 43, 45-48], Thornthwaite [43, 49], and Hamon

[43, 50] methods. The methods were checked against the widely used spreadsheet from UC Davis "PMDay.xls" [44] to confirm the calculations.

Table 2: Inputs required for each evapotranspiration method tested

ET Method	Temperature	Humidity	Radiation	Other
Hamon	Mean			Day length
Hargreaves-Samani	Min, max		Extraterrestrial	
Penman-Monteith	Min, max	Min, max	Extraterrestrial, incoming solar	Wind speed, atmospheric pressure
Thornthwaite	Mean			Day length

The Penman-Monteith equation can take several forms; this paper follows the procedure laid out in The ASCE Standardized Reference Evapotranspiration Equation [30], where it is defined as:

$$ET_{sz} = \frac{0.408\Delta(R_n - G) + \frac{C_n}{T + 273} u_2(e_s - e_a)}{\Delta + \gamma(1 + C_d u_2)}$$

C_n and C_d are constants that determine whether the equation is calculating reference ET for alfalfa (ET_{rs}) or reference ET for clipped grass (ET_{os}). For a daily timestep for the short reference crop (clipped grass), C_n is 900 °K-mm-s^3 / Mg-day, and C_d is 0.34 s/m. G, the soil heat flux density, was neglected due to the use of a daily timestep. The psychrometric constant, γ, equals 0.000665 times the pressure in kPa. Δ is the slope of the saturation vapor pressure-temperature curve and has the equation:

$$\Delta = \frac{2503 exp(\frac{17.27T_{max}}{T_{max} + 237.3})}{(T + 237.3)^2}$$

Most necessary inputs were supplied by the HPRCC automated weather stations. The Saturation vapor pressure, e_s, was calculated based on daily minimum and maximum temperatures. Actual vapor pressure, e_a, for the Penman-Monteith method was calculated using the daily minimum and maximum relative humidity measurements.

$$e_a = \frac{0.6108exp(\frac{17.27T_{min}}{T_{min} + 237.3})\frac{RH_{max}}{100} + 0.6108exp(\frac{17.27T_{max}}{T_{max} + 237.3})\frac{RH_{min}}{100}}{2}$$

$$e_s = \frac{(0.6108exp\frac{17.27T_{min}}{T_{min} + 237.3}) + (0.6108exp\frac{17.27T_{max}}{T_{max} + 237.3})}{2}$$

Net radiation is dependent on the net incoming shortwave and the outgoing longwave radiation, which in turn are dependent on location, time of year, vapor pressure, and temperature. R_s is reported by the HPRCC weather stations as the parameter "SolarRad", and R_a, necessary for both the Penman-Monteith and the Hargreaves-Samani models, was calculated based on latitude and day of the year [30, 45, 51].

$$R_n = R_{ns} - R_{nl}$$

$$R_{ns} = 0.77R_s$$

$$R_{nl} = \sigma\left(1.35\frac{R_s}{R_{so}} - 0.35\right)\left(0.34 - 0.14\sqrt{e_a}\right)\left[\frac{{T_{K,max}}^4 + {T_{K,min}}^4}{2}\right]$$

$$R_{so} = (0.75 + 2 \times 10^{-5}z)R_a$$

$$R_a = \frac{24}{\pi}4.92\left(1 + 0.033\cos\frac{2\pi J}{365}\right)[\omega_s \sin\varphi \sin\delta + \cos\varphi \cos\delta \sin\omega_s]$$

$$\delta = 0.409\sin\left(\frac{2\pi J}{365} - 1.39\right)$$

$$\omega_s = \cos^{-1}(-\tan\varphi \tan\delta)$$

Average daily evapotranspiration was plotted for each method. The Penman-Monteith equation was calculated with all data from the weather stations and also with a cap on wind speed (at 5.1 m/s) and vapor pressure deficit (e_s-e_a; at 2.1 kPa) as suggested in Hubbard 1992 [52-53].

Despite the widespread use and acceptance of the Penman-Monteith evapotranspiration model, a different model needs to be used due to the large amount of inputs Penman-Monteith requires and the limited number of weather stations able to provide those inputs. If a simpler model could perform as well or nearly as well as the Penman-Monteith model, then that model could be used for locales with simpler weather stations, and not just in locations near the sites of the 14 automated HPRCC weather stations. The Hargreaves-Samani evapotranspiration method was developed as an alternative to the input-intensive Penman-Monteith method [46-48] and is used commonly in agriculture and irrigation engineering. Daily temperature is available at far more locations than wind speed and relative humidity, so this method will be used to calculate reference ET across the state. Additionally, using a model that relies on fewer inputs than the Penman-Monteith could allow for easier prediction of future irrigation demands. Changes in temperature could be predicted based on IPCC projections, but how windspeed, humidity, or cloudcover might be affected by climate change is less clear.

The procedure for calculating evapotranspiration using the Hargreaves-Samani method will be the same as that found in The ASCE Standardized Reference Evapotranspiration Equation [30]. This method calculates a grass reference evapotranspiration and uses a daily timestep.

$$ET_0 = 0.0023(T_{max} - T_{min})^2\ (T_{mean} + 17.8)\ R_a$$

As can be seen in Figure 16, the reported evapotranspiration by the HPRCC appears to overestimate the actual evapotranspiration as calculated by the Penman-Monteith method. The Hargreaves-Samani method slightly underestimates reference ET at this location. The suggested caps on vapor pressure deficit and wind speed do not significantly alter evapotranspiration. Thornthwaite and Hamon both underestimate evapotranspiration even more than Hargreaves-Samani. Thornthwaite commonly underestimates evapotranspiration in arid conditions [43, 54], such as the High Plains region, and Hamon has also been found to underestimate reference evapotranspiration [55].

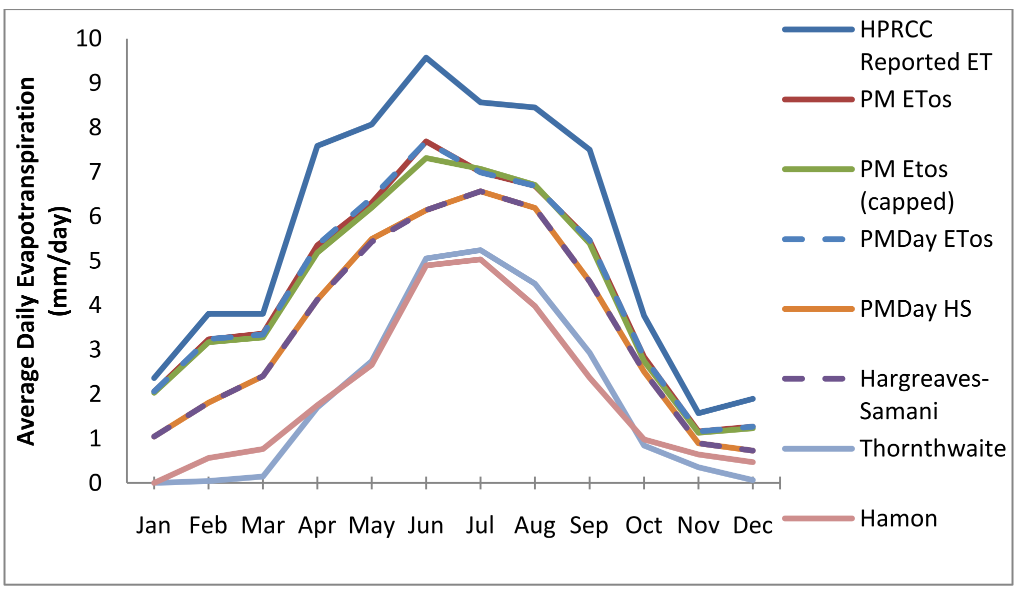

Figure 16: Average daily evapotranspiration by month at Colby, KS, 2000. PM ET_{os} is the calculated grass reference evapotranspiration, PM ET_{os} (capped) includes caps to windspeed and vapor pressure deficit as described previously, PMDay ET_{os} is grass reference ET as calculated by the PMDay spreadsheet, and PMDay HS is the Hargreaves-Samani evapotranspiration as calculated by the PMDay spreadsheet.

The same analysis on other locations yields similar results. The primary difference at Garden City (Figure 17) is that the Hargreaves-Samani reference evapotranspiration is closer to the Penman-Monteith reference ET than it was at Colby.

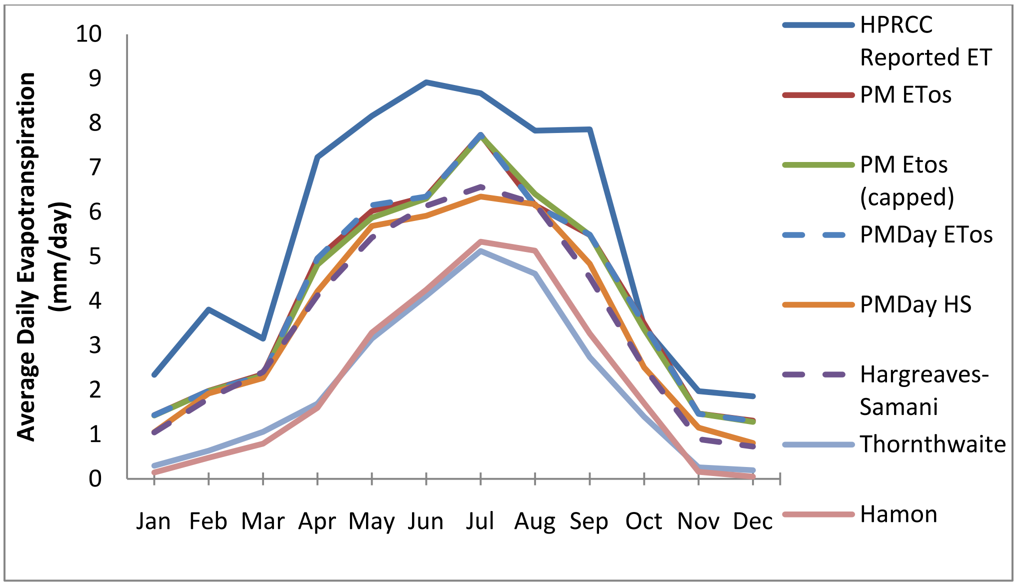

Figure 17: Average daily evapotranspiration by month at Garden City, KS, 2000

Figure 18 shows the difference between the Penman Monteith evapotranspiration model and the Hargreaves Samani model. Values were included for the months of April through October for the years 1988 through 2009. The HPRCC reported ET values tend to overestimate reference evapotranspiration, especially on the high end, whereas the Hargreaves Samani reference evapotranspiration plots exhibit more spread in the data and, in some locations, tend to underestimate evapotranspiration on the high end.

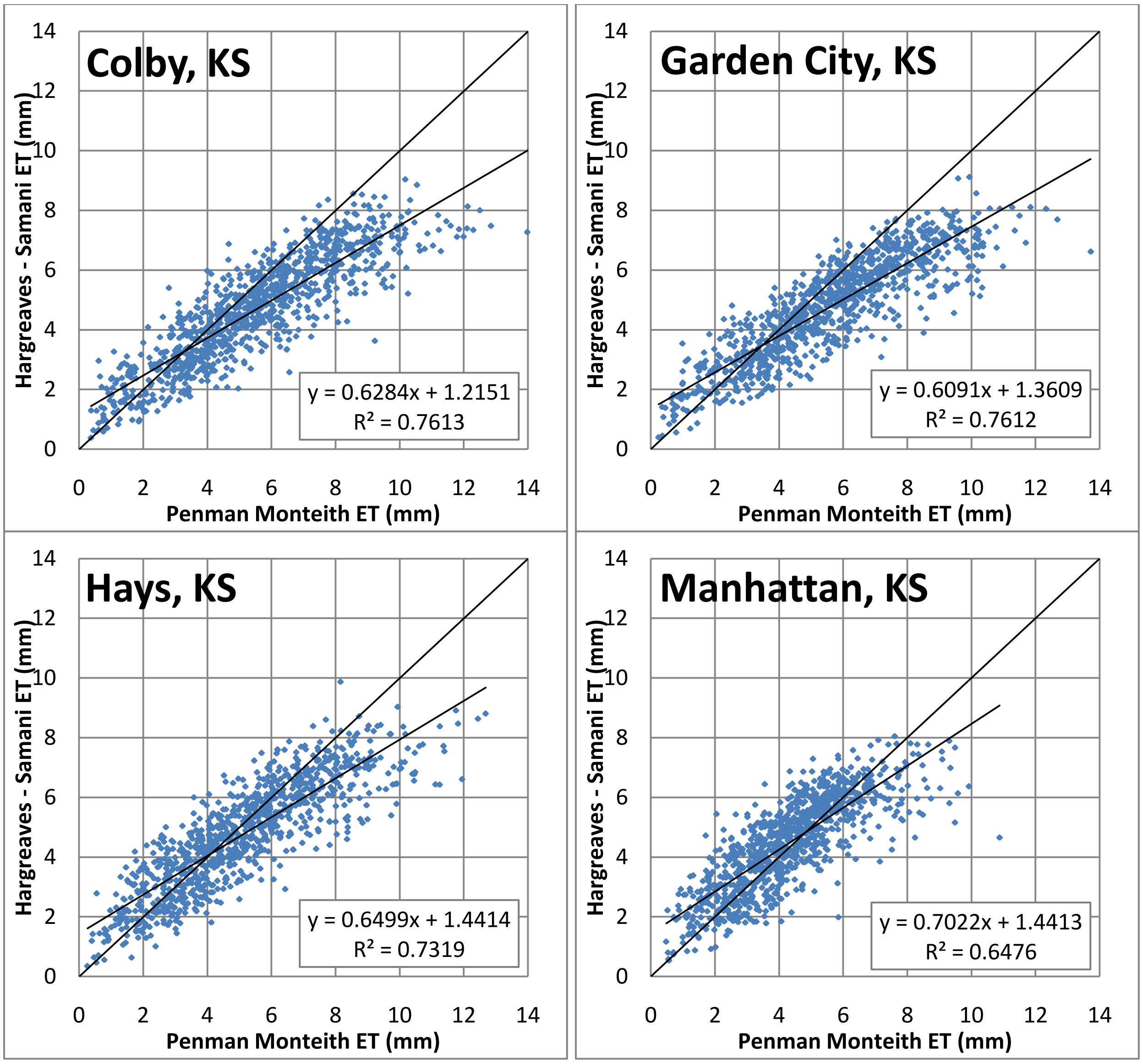

Figure 18: Scatter plot of the difference between Penman Monteith evapotranspiration and Hargreaves Samani evapotranspiration at four locations in Kansas. A random 1000 daily ET values from the growing seasons 1988-2009 are included in each plot.

Figure 19 shows the differences between the Penman Monteith reference evapotranspiration and the Hargreaves Samani reference evapotranspiration at all four locations where data were available. If a systematic, state-wide correction were to be applied to the Hargreaves-Samani equation, a relationship could be derived from a composite sample of all four weather stations. A systematic correction of the Hargreaves-Samani evapotranspiration model was not performed because lysimeter data were not available in Kansas. Two correlations of the data are presented in Figure 19: a linear regression and a quadratic regression.

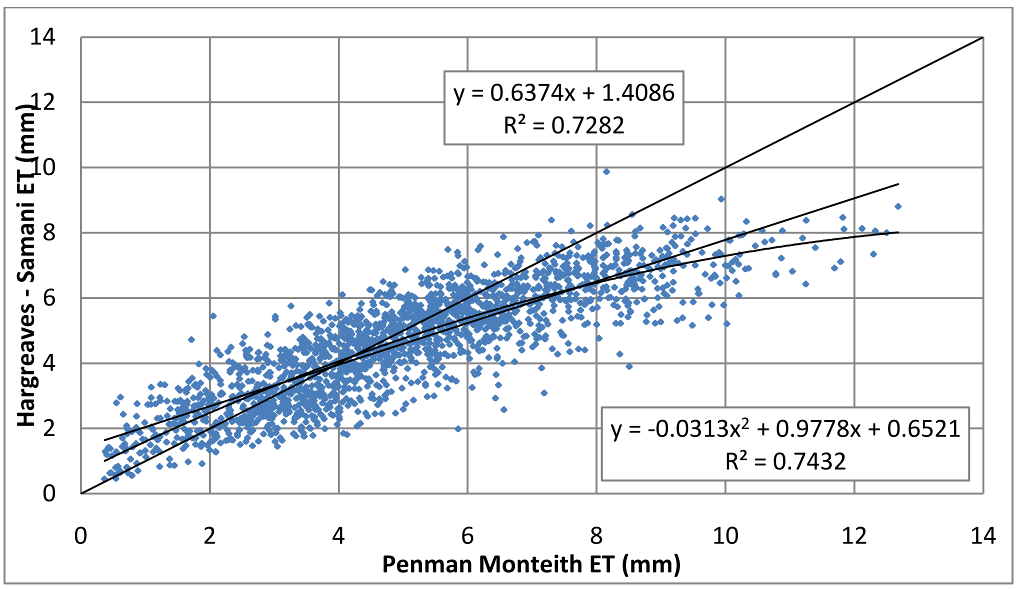

Figure 19: Scatter plot of the difference between Penman Monteith evapotranspiration and Hargreaves Samani evapotranspiration for all four locations in Kansas. A random 500 daily ET values from the growing seasons 1988-2009 are included from each station.

Crop Coefficient Scaling

There are several methods for converting reference evapotranspiration to an actual amount of water consumed by a crop (ET_c). One method is to adjust the albedo and surface resistances in the Penman Monteith equation and calculate crop evapotranspiration directly, but these parameters are difficult to estimate and change throughout the growing season [56]. The approach used for this analysis is the crop coefficient approach, a method which is much simpler and more widely used. In this method, the reference evapotranspiration is multiplied by a crop coefficient, K_c, that varies based on the growth stage of the plant [30, 56-59]. ET_c is calculated as shown below:

$$ET_c = K_c * ET_0$$

Different methods exist for determining K_c. One method consists of the breaking down of the growing season into several growth stages based on days after planting, with a different K_c for the initial, middle, and end of the growing season [56, 60]. Additionally, K_c can be determined based on cumulative growing degree days (GDD) [57-58, 61]. Each crop variety is considered mature when it reaches a certain total value. The equation for one day's accumulation of GDD is

$$GDD = \frac{T_{max} + T_{min}}{2} - T_{Base}$$

Growing degree days only accumulate when the average temperature is above T_{Base}. If $(T_{max} + T_{min})/2 < T_{Base}$, then GDD = 0 [61], i.e., if the average temperature for a day is below the base temperature, then no growing degree days are accumulated on that day. Higher temperatures generally result in a faster rate of accumulation of GDD, but there is also an upper limit, above which there is no further benefit. This cap is specific to each crop. If $T_{max} > T_{Peak}$, then $T_{max} = T_{Peak}$.

Each crop matures and acquires growing degree days at a different rate. Table 3 shows the minimum temperature (T_{Base}), the upper cap on T_{Max} (T_{Peak}), the cumulative GDD at which irrigation stops, and the cumulative GDD at harvest for each crop [57].

Table 3: Crop-specific parameters for calculating growing degree days (GDD)

Crop	Baseline Temperature (°C)	Peak Temperature (°C)	GDD at halting irrigation	Minimum GDD at harvest
Corn	10	30	1530	1890
Sorghum	10	37.8	1230	1830
Soy	7.8	30	1780	1890
Winter Wheat	0	26.1	2470	2970

For example, if the high for one day was 35°C, and the low was 20°C, a field planted in sorghum would accumulate 17.5 GDD for that day: (35+20)/2 – 10. Corn, however, has a lower tolerance for heat, so the maximum temperature would be capped at 30°C. It would only accumulate 15 GDD for that day.

Crop coefficients for different developmental stages were obtained for three crops (corn, sorghum, and soy) from the Texas High Plains Evaporation Network [57-58]. The Bushland, TX experiments used a longer season corn variety (Harvest at 2111 heat units) [58] than is otherwise used in Kansas, so the crop coefficients are scaled based on a shorter growing season (1890 heat units) [57]. Sorghum, soy, and wheat were all similarly scaled. Table 4 includes the crop coefficient for several developmental stages of corn and the accompanying original and scaled heat unit value. The full tables are located in Appendix C.

Table 4: Sample from Kc - GDD table for Corn

Crop Stage	Kc	GDD (°C-d)	Adjusted GDD (°C-d)
Seeded	0.25	111	99
Emerged	0.35	194	173
4-leaf	0.45	286	256
4-leaf	0.7	375	335
6-leaf	0.85	472	422
…	…	…	…
Harvest	0	2111	1890

Crop coefficients based on accumulated heat units for wheat were unavailable for a grass-based reference ET, but they were available for an alfalfa-based ET [62]. By using the HPRCC stations, both grass- and alfalfa-based evapotranspiration can be calculated, and the ratios of ET_{rs}

to ET_{os} (K_r) throughout the year can be determined [45, 52, 63]. Figure 20 shows the daily value for K_r for four HPRCC weather stations. Approximately 500 values for each weather station are plotted based on daily ET values from 1990 through 1995. At each location, the ratio averaged approximately 1.4 throughout the year, with more variation in winter, when ET is at a minimum. Since $K_r=ET_{rs}/ET_{os}$, and $ET_c = K_{c(alfalfa)}*ET_{rs}$, crop evapotranspiration can be calculated with the following equation.

$$ET_c = K_r K_{c(alfalfa)} ET_{os}$$

Therefore, the K_c for wheat for a grass-based ET method is 1.4 times the reported alfalfa-based crop coefficient. The value for K_r varies by location; previous studies have estimated K_r to be between 1 and 1.5, depending on the method, location, and time [45, 52, 63]. Clay Center, Nebraska found a K_r of 1.43 for the entire year and 1.35 for the growing season (which was considered to be May 1 through September 30) [52].

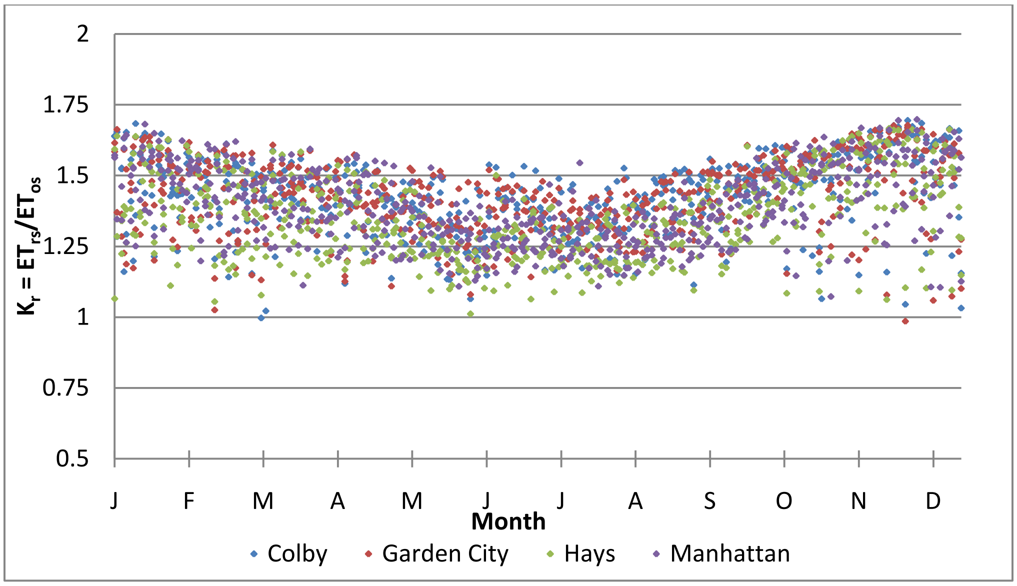

Figure 20: ET_{rs}/ET_{os} at various locations in Kansas

The majority of published crop coefficients for wheat are based on days after planting or percent of growing season [64]. These time-based crop coefficients had ranges that were similar to the curve created from scaling the alfalfa-based crop coefficient values [59, 64-65].

Figure 21 shows the K_c over the entire growing season for each crop for the adjusted growing season. In each case, K_c starts out as zero or very low and rises as the crop develops and matures. It reaches a peak midway through the growing season and then drops again as the crop nears harvest. Because there is still evaporation from bare ground, it is unreasonable to have an actual evapotranspiration equal to 0, which is what would occur if $K_c = 0$. To avoid this case, a minimum value of 0.18 is used for K_c in the water budget. It is estimated that approximately one fifth of the reference ET is assumed to evaporate from bare ground [60].

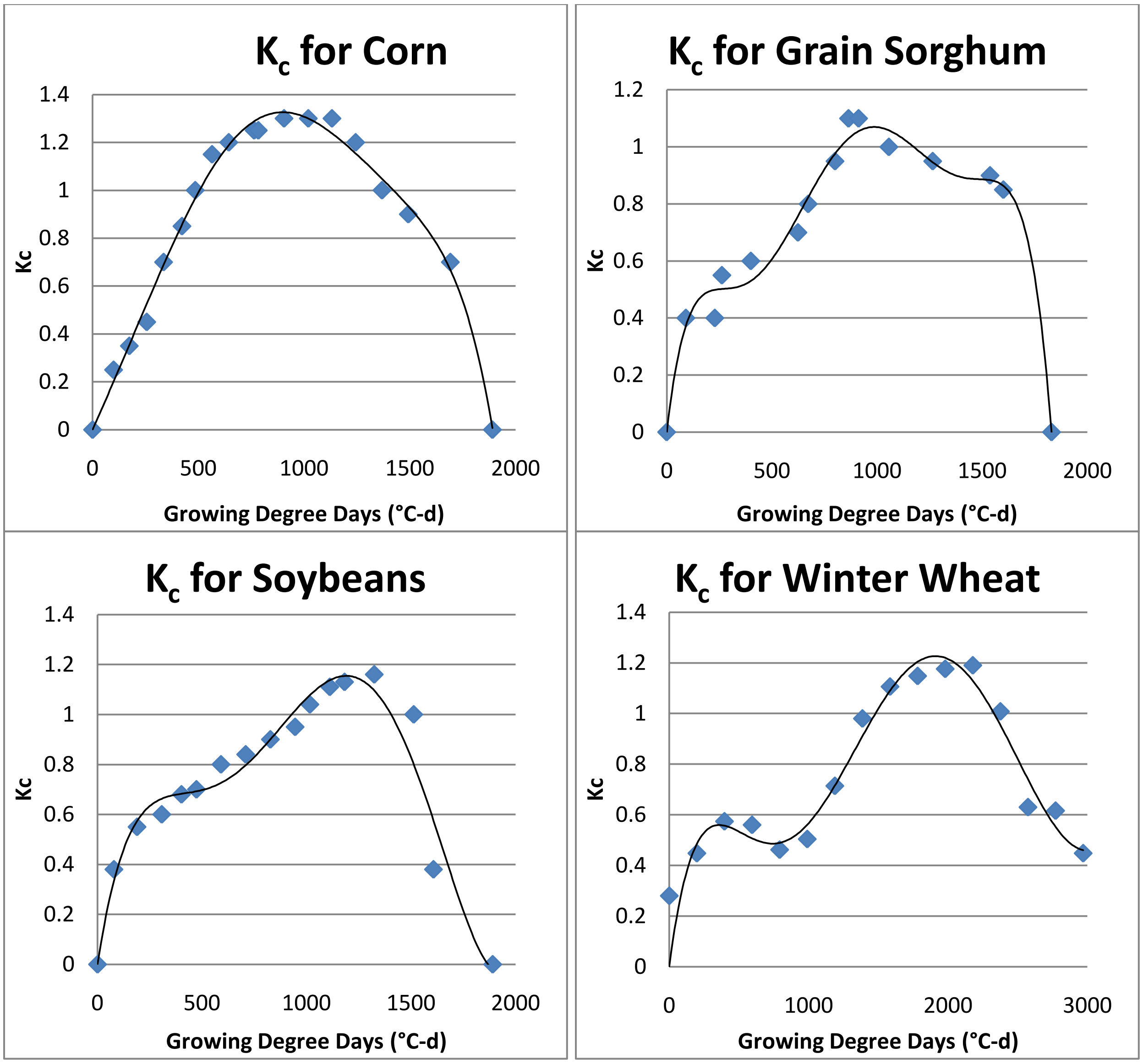

Figure 21: K_c vs growing degree days by crop

Table 5: Regression equations for each crop type

Crop	Equation	r^2
Corn	$y = -1E-18x^6 + 4E-15x^5 - 6E-12x^4 + 2E-09x^3 + 7E-08x^2 + 0.002x$	0.9921
Sorghum	$y = -7E-18x^6 + 4E-14x^5 - 7E-11x^4 + 7E-08x^3 - 3E-05x^2 + 0.0064x$	0.9816
Soy	$y = 3E-15x^5 - 1E-11x^4 + 2E-08x^3 - 2E-05x^2 + 0.0054x$	0.9508
Wheat	$y = -1E-19x^6 + 1E-15x^5 - 6E-12x^4 + 1E-08x^3 - 1E-05x^2 + 0.0042x$	0.9159

To estimate the crop coefficient as the growing season progresses, a fifth or sixth order polynomial regression was performed for each K_c plot. With these regression equations, the accumulated growing degree days can be tracked throughout the growing season to determine a daily K_c for each crop. The regression equations for these crop coefficient plots are shown in Table 5.

Validation of a Water Budget Model for Estimating Irrigation Demand

The irrigation demand for each crop is calculated using a water budget method. This analysis uses a water budget model drafted by Johannes Feddema of the University of Kansas. The original water budget model was altered for this project. The Hargreaves-Samani evapotranspiration equation was added to the model, as well as growing degree day calculations, crop coefficient scaling of reference ET, and irrigation scheduling based on soil moisture conditions.

The water budget model operates under the governing idea that inputs of water to a system minus the withdrawals equal the change in water stored in that system. This can be applied to an irrigated field in order to track the available soil moisture to determine the irrigation water needed. The inputs to this system are precipitation and irrigation, and water is removed via evapotranspiration and runoff. The difference between the inputs and the outputs is the change in water storage in the soil.

$$\Delta ST = P + I - ET - R$$

Each location requires the input of latitude and water holding capacity. The water holding capacity was calculated using the SSURGO soils database and is the spatially-weighted average of the SSURGO attribute aws0100wta across all land that was categorized as Cultivated Crops in each county. This parameter is the total depth of water that the soil can store above the wilting point aggregated over a depth of 100 cm. This measurement is also available for the additional depths of 25 cm, 50 cm, and 150 cm [66], but 100 cm was chosen to match a root zone of 3 feet for corn, according to the Kansas State University Mobile Irrigation Lab. [29]. The land use dataset to determine the area of cultivated land was the National Land Cover Dataset from the NRCS from 2001 [67].

Any precipitation is divided into runoff or infiltration using the SCS curve number method. The curve number in each water budget calculation was estimated using the hydrologic soil group of the agricultural area of each county, also from SSURGO. The land use was assumed to be cultivated land with conservation treatment. After runoff is calculated, the effective precipitation is compared to the potential crop evapotranspiration to calculate the impact on soil water content. The average water holding capacity for 100 cm and curve number for the agricultural areas of each of the target counties are shown in Table 6.

Table 6: Water Holding Capacity and Curve Number for each of the target counties

County	Water Holding Capacity (mm)	Curve Number
Barton	150	72.8
Finney	178	74.8
Morton	140	71.1
Pawnee	169	74.1
Reno	149	75.4
Stafford	144	75.0
Stevens	142	70.7
Thomas	200	72.9
Wichita	192	73.9

Using daily temperature data and information about the location, the model calculates reference evapotranspiration using one of the Thornthwaite, Hamon, or Hargreaves-Samani methods and can then scale it using growing degree day crop coefficients to determine daily potential evapotranspiration. When available soil moisture is low, evapotranspiration becomes limited and the potential ET cannot be reached. The water budget assumes that as moisture is removed from the soil, it becomes incrementally harder to remove additional water. Actual evapotranspiration is calculated based on the previous day's soil moisture content according to the following equation.

$$AE_n = \frac{ST_{n-1}}{WHC} * PE$$

Table 7 shows the crop-specific inputs for the water budget model. Each crop has a different planting date and harvest date [68-69]. If the crop reaches the cumulative growing degree days required for harvest [57] prior to this end harvest date, then it is considered ready for harvest and the water budget model stops calculating the water deficit. Each crop also has different tolerances for heat and cold [57], so different upper and lower limits on temperature for calculating GDD are supplied for each crop. To minimize waste of water and maximize the capture of off-season precipitation, scheduled irrigation (if utilized; described later) halts once the crop reaches a certain growing degree day cap.

Table 7: Crop-specific parameters for the water budget model

	Corn	**Sorghum**	**Soy**	**Winter Wheat**
Start of Growing Season (Day of Year)	April 10 (100)	April 25 (115)	May 5 (125)	September 15 (258)
End of Growing Season (Day of Year)	November 5 (304)	November 10 (309)	November 5 (304)	July 10 (191)
Base Temperature	10	10	7.8	0
Peak Temperature	30	37.8	30	26.1
GDD at Termination of Irrigation	1530	1230	1780	2470
GDD at Harvest	1890	1830	1890	2970

Results of the Water Budget Validation

The water budget was run for the target counties using either the HPRCC weather or the long term stations to calculate the moisture deficit over the entire growing season. The deficit was calculated independently for each major crop before being multiplied by the irrigated acreage for that crop (acreage provided by NASS). A sample of the irrigated areas and moisture deficits for Thomas County is included in Table 8. The remainder of the water budget results and calculations can be found in Appendix D.

Table 8: Irrigated areas and moisture deficit for Thomas County

Year	Area Planted in Corn (Acres)	Area Planted in Sorghum (Acres)	Area Planted in Soy (Acres)	Area Planted in Wheat (Acres)	Deficit for Corn (mm)	Deficit for Sorghum (mm)	Deficit for Soy (mm)	Deficit for Wheat (mm)
1992	50,600	5,100	5,300	7,000	325	200	132	1,230
1993	60,200	3,500	3,500	9,800	310	204	176	1,150
1994	66,300	1,000	3,900	9,800	461	332	210	1,190
1995	64,800	1,900	3,700	9,700	346	232	184	959
1996	65,500	2,900	4,000	7,900	239	131	102	1,190

Another important parameter is irrigation efficiency, which is how much of the applied water actually goes towards replenishing the soil moisture zone. Irrigation efficiency was assumed to be 90% [29, 70-72], but this estimate could be further refined with additional information about regional irrigation practices. To get irrigation need for the county in acre-feet, the following equation was used:

$$\begin{bmatrix} Irrigation\ Need \\ (acre-feet) \end{bmatrix} = \frac{[Moisture\ Deficit\ in\ mm]}{25.4\ mm/in * 12\ in/ft} * \frac{[Area\ in\ Acres]}{[Irrigation\ Efficiency]}$$

This calculated irrigation demand (shown in Table 9 for Thomas County for 1992-1996) was then compared to the reported irrigation water use in WIMAS. As can be seen in the figures below, in which the results for all counties from 1986 through 2007 are shown, the calculated demand is compared to the reported irrigation water use. As can be seen in Figure 22, there is a good correlation between the predicted water use and the reported water use.

Table 9: Calculated irrigation need by crop in Thomas County

Year	Corn (acre-ft)	Sorghum (acre-ft)	Soy (acre-ft)	Wheat (acre-ft)	Total (acre-ft)
1992	59,930	3,722	2,541	31,418	108,457
1993	68,083	2,605	2,243	41,225	126,841
1994	111,401	1,212	2,986	42,381	175,533
1995	81,698	1,603	2,486	33,905	132,991
1996	57,072	1,381	1,490	34,334	104,752

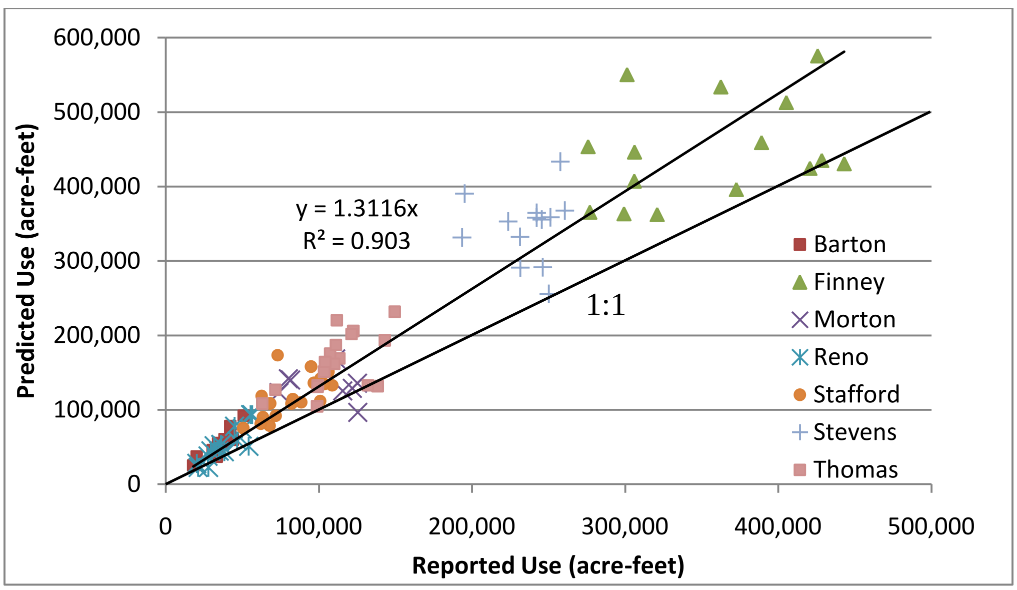

Figure 22: Plot of Predicted use based on evapotranspiration versus reported use from WIMAS. This plot is based on data from Barton, Finney, Morton, Reno, Stafford, Stevens, and Thomas counties. Years where NASS irrigated acreage was missing are omitted from this regression.

Figure 23 indicates that error seems to be evenly distributed among the range of values, not concentrated at the low or high end. The model is regularly overestimating water consumption. This overestimation could potentially be explained by a technological limitation where pumping cannot supply water as quickly as the field is using it [29].

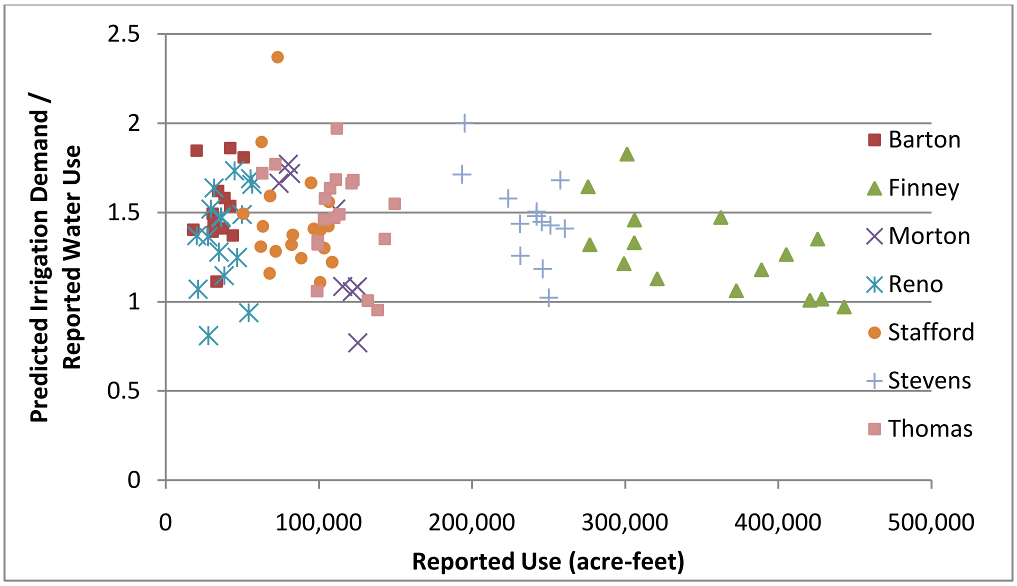

Figure 23: Comparison of predicted use to reported use. Values greater than 1 indicate an overestimate of water use.

The water balance was then run again with several additional restrictions. A maximum feasible irrigation rate was determined by dividing a theoretical maximum pumping rate by the area that is irrigated. Over 90 percent of irrigated cropland in Kansas is irrigated using a center pivot irrigation system [73]. A standard center pivot irrigation system is a quarter mile long [72-77], which means it can irrigate approximately 125 acres. Assuming a reasonable (based on analysis of WIMAS pumping rates and conversations with drilling contractors) maximum pumping rate of 800 gpm [35, 75-77], the daily maximum irrigation rate is 12 mm per day. If the daily water demand is higher than the maximum irrigation rate, then that day's demand is capped at the maximum rate.

In addition to the technological limitation where pumping rate may not keep up with evapotranspiration, a county might run up against the legally binding limitation on the amount of water allowable for use. For each county, the maximum water right for each year was calculated based on data from WIMAS. If the required irrigation water was higher than the total amount of irrigation water authorized, then the predicted use was capped at the authorized amount. The comparison of reported water use to predicted water use, capped by maximum rate and legally binding limitations on withdrawal, is shown in Figure 24. When these limitations are included in the analysis, the slope and correlation both improve.

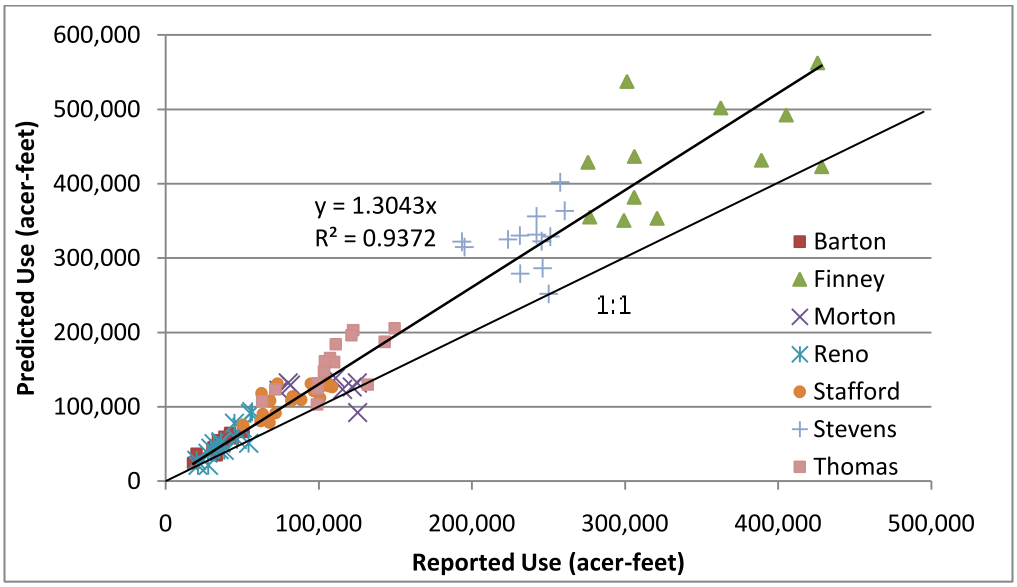

Figure 24: Plot of predicted use based on evapotranspiration versus reported use from WIMAS. This reported use is limited based on both the maximum legally binding limitation on groundwater withdrawal and a maximum pumping rate. Years where NASS irrigated acreage was missing are omitted from this regression.

After the addition of the legally binding limitation on water use, the correlation further improves, especially at the lower end. However, this approach only limits the volume of irrigation water used at the county level. It would be possible for some irrigation wells to run up against their legal limits while others, and the county as a whole, were withdrawing less than their authorized quantity. A more accurate approach would be to apply this limitation at each individual point of diversion.

An alternative method for determining the irrigation rate would be to model irrigation directly in the water budget. The amount of irrigation water applied is determined based on soil water storage and moisture deficit. A general irrigation guideline is to maintain at least 50% saturation in the root zone [29, 77]. The water budget scheduled irrigation to begin whenever soil water storage goes below 50% and to continue until it reaches 75% saturation based on recommendations from the Kansas State University Mobile Irrigation Lab. Irrigation was applied at a maximum rate of 12 mm/day, as explained above, and summed to calculate the yearly application amounts. The results of this new water budget are shown in Figure 25 and Figure 26: the model is no longer over predicting water use by 30% across the board. Rather, the model is now able to estimate water use much closer (a slop of 1.015) to the actual reported use than before, when irrigation rate was determined by using the moisture deficit over the growing season.

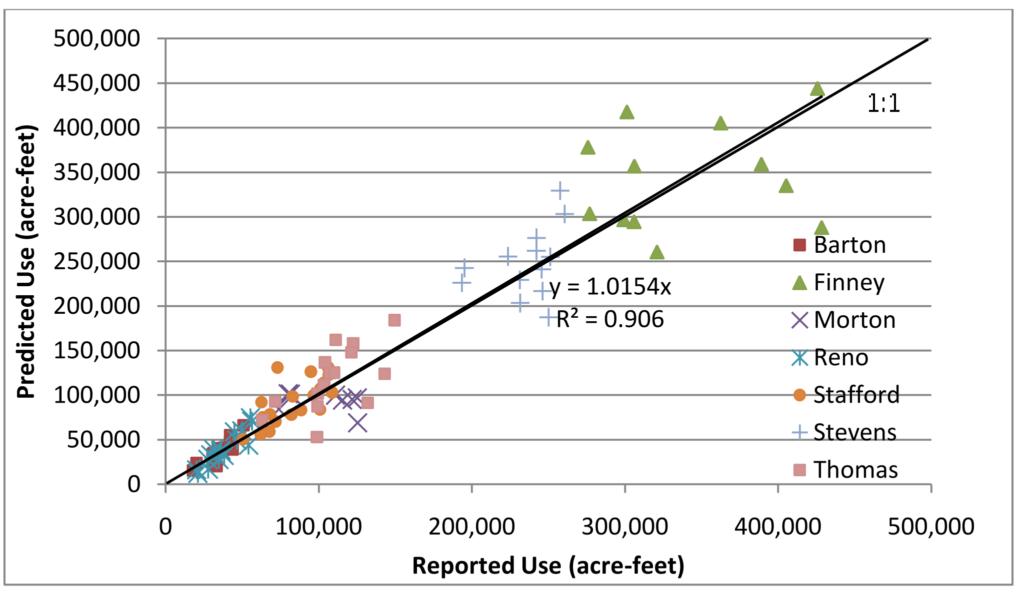

Figure 25: Plot of predicted use based on scheduled irrigation versus reported use from WIMAS.

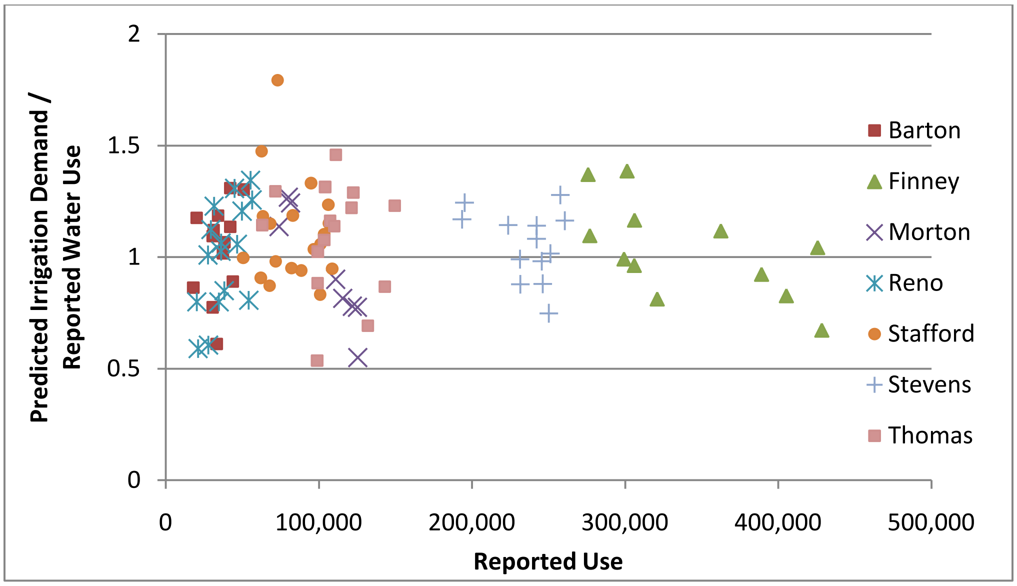

Figure 26: Comparison of predicted use to reported use. Values greater than 1 indicate an overestimate of water use.

Figure 27 through Figure 30 show the required, used, and authorized quantities of irrigation water for selected counties, in addition to the error for each year.

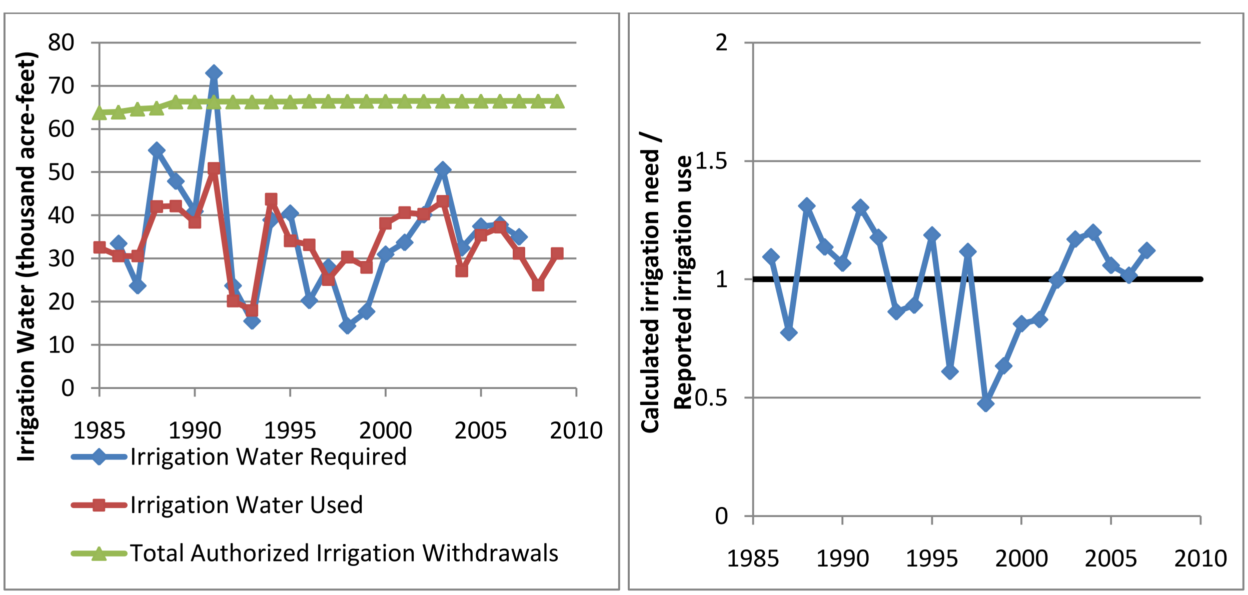

Figure 27: Comparison of predicted need to reported use in Barton County

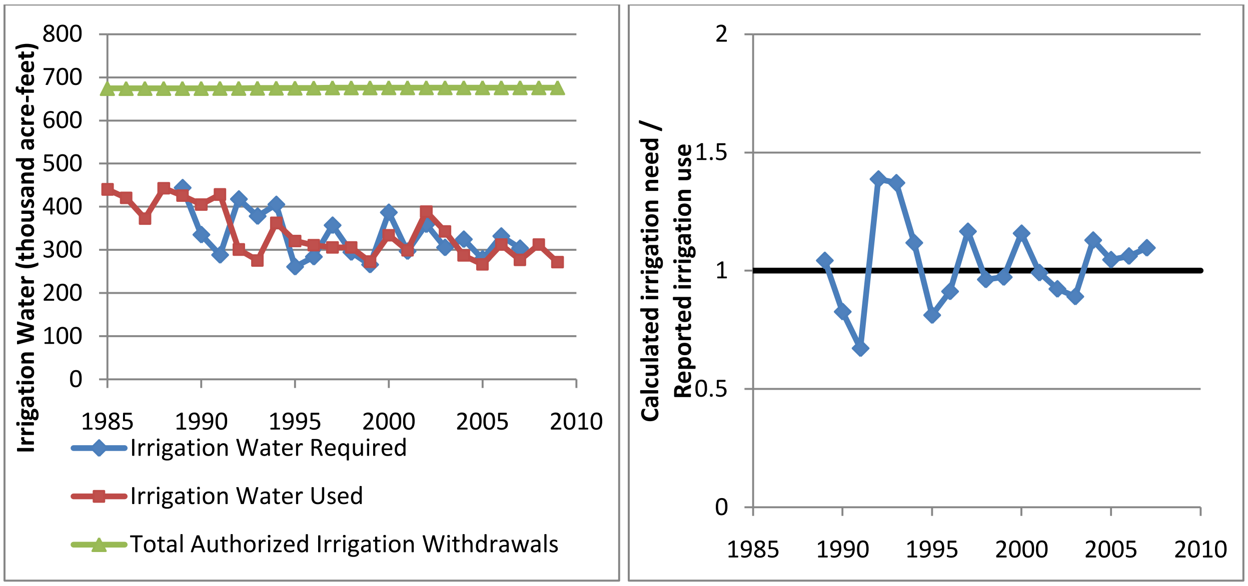

Figure 28: Comparison of predicted need to reported use in Finney County

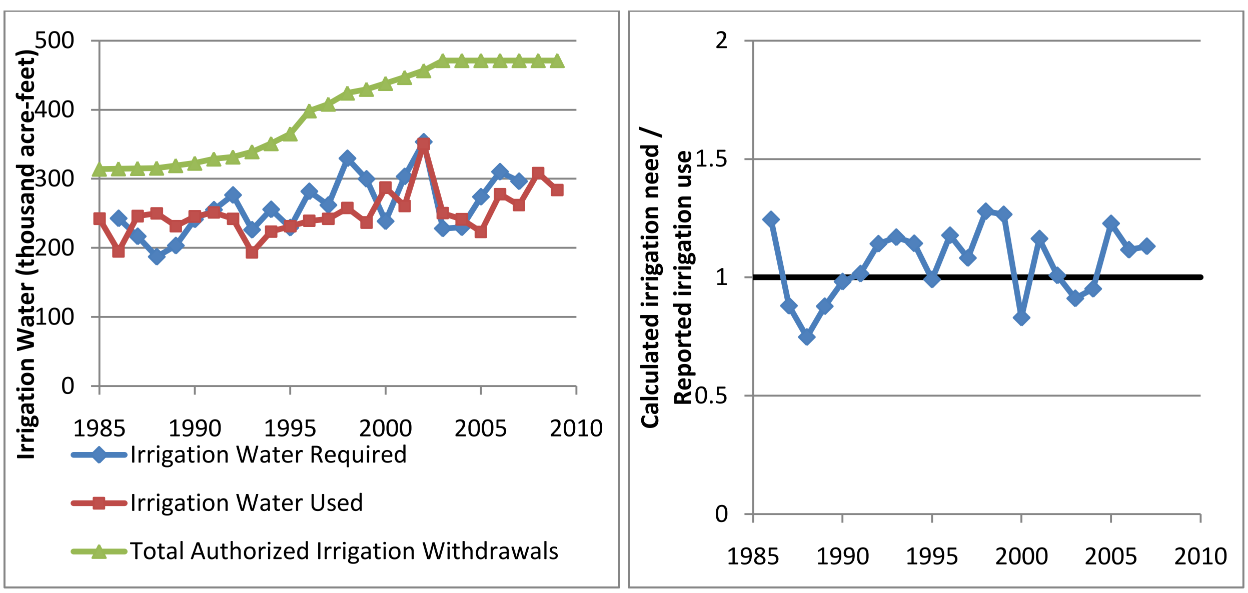

Figure 29: Comparison of predicted need to reported use in Stevens County

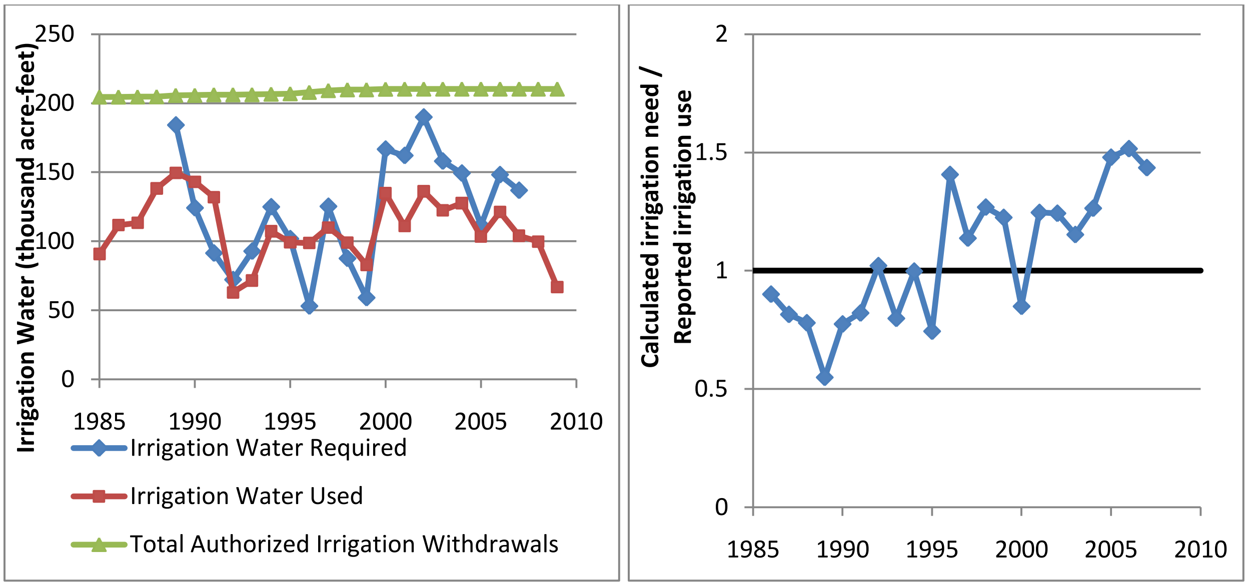

Figure 30: Comparison of predicted need to reported use in Thomas County

Only two counties have their predicted need capped by the authorized available water: Barton County in 1991 (Figure 27) and Stafford County in 2003 and 2007 (not shown).

The Impact of Climate Change on Irrigation

Temperature and precipitation for each county were scaled seasonally according to the median IPCC model projection. Table 10 summarizes this projection for the region CNA. This projection is how the average temperature and precipitation of 2080-2099 will change from the average of 1980-1999. The entire year sees an increase in mean temperature. Precipitation is predicted to also increase for most of the year, but June through August is predicted to experience less precipitation.

Table 10: Median IPCC model projection for the change in temperature and precipitation over 100 years. DJF is December, January, February.

	DJF	MAM	JJA	SON	Annual
T (Plus °C)	3.5	3.3	4.1	3.5	3.5
Precipitation (% Change)	5	7	-3	4	3

Using data from 1985 through 2010, the climate data was adjusted based on this 100 year projection to create a climate prediction for 2085 through 2110. Using this adjusted climate data, the water budget model was used to predict irrigation need. Irrigation need was estimated using both approaches: moisture deficit over the growing season and scheduled irrigation based on soil moisture. This procedure was performed for Finney, Reno, and Thomas Counties in order to get an example of high, low, and moderate annual water use.

Figure 31 through Figure 33 show the moisture deficit for each county (with and without climate change), the predicted irrigation water use (with and without climate change), the maximum allowable withdrawals for each year, and the reported water use for each year. In each case, the predicted need after a climate change scenario has been implemented is less than the predicted need with the actual weather data.

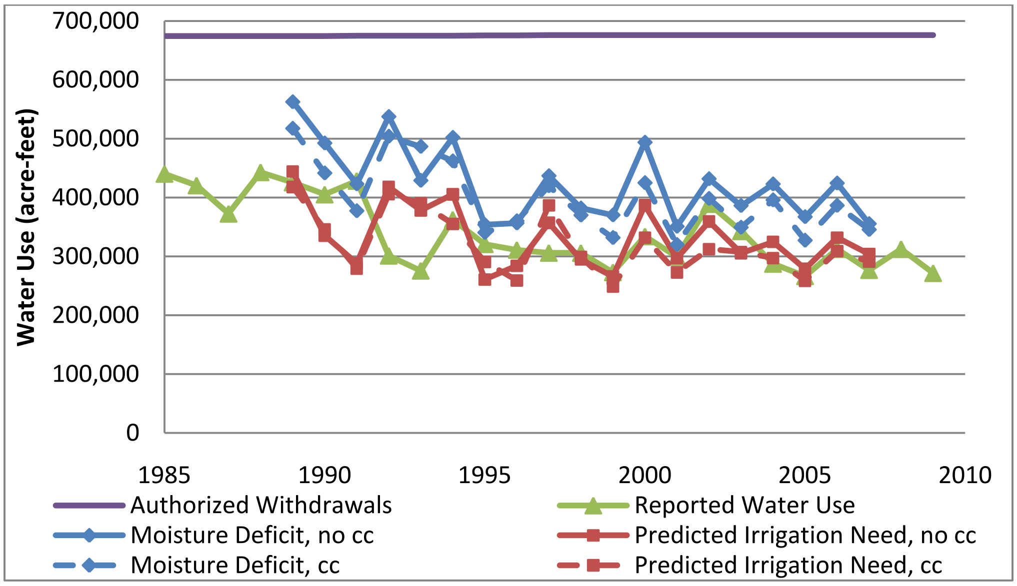

Figure 31: Irrigation in Finney County, with and without climate change

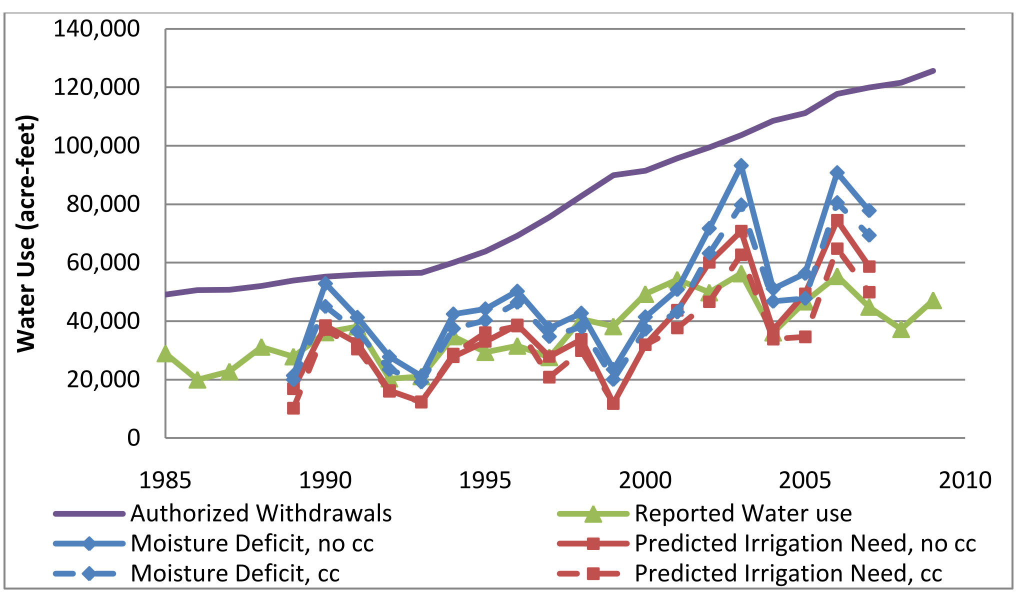

Figure 32: Irrigation in Reno County, with and without climate change

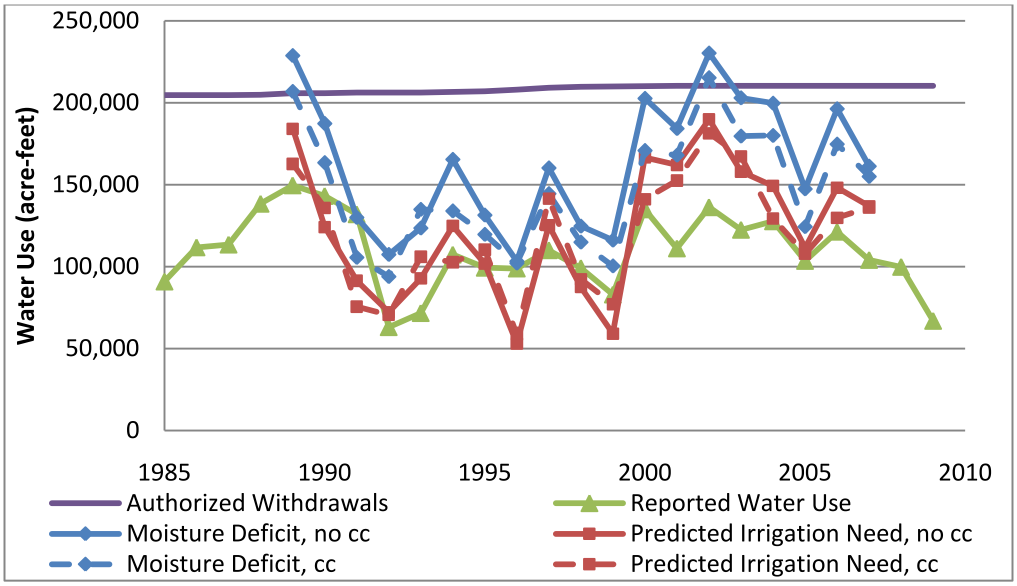

Figure 33: Irrigation in Thomas County, with and without climate change

Table 11 shows the ratio the climate change scenario to the base scenario of the moisture deficit for reference ET, the irrigation need based on moisture deficit by crop, and irrigation need based on scheduled irrigation to maintain soil moisture conditions. For each county, the average moisture deficit for the reference ET was higher in the climate change scenario than in the base scenario. However, the predicted irrigation need for each county under climate change was less than the historic predicted irrigation need in all cases.

Table 11: Ratio of value for climate change scenario to value original weather data for the moisture deficit for reference ET over the growing season, irrigation need from moisture deficit over the growing season, and the irrigation requirement based on scheduled irrigation. These values are the average of each year from 1989 – 2007

	Moisture Deficit for Reference ET (mm)	Irrigation Requirement from Moisture Deficit (acre-ft)	Irrigation Requirement from Scheduled Irrigation (acre-ft)
Finney County	1.150	0.937	0.961
Reno County	1.177	0.885	0.899
Thomas County	1.150	0.901	0.996

Under the climate change scenario, none of the parameters in the water budget were changed except for temperature and precipitation. The planting dates, required growing degree days for maturity, and temperature thresholds for each crop were the same. Since the increased temperature increases the amount of growing degree days acquired each month (Figure 34), but the number of GDD required for crop maturity was assumed to remain constant, each crop reaches maturity faster under the climate change scenario than in the base case. This means that there is less time available for irrigation to be applied.

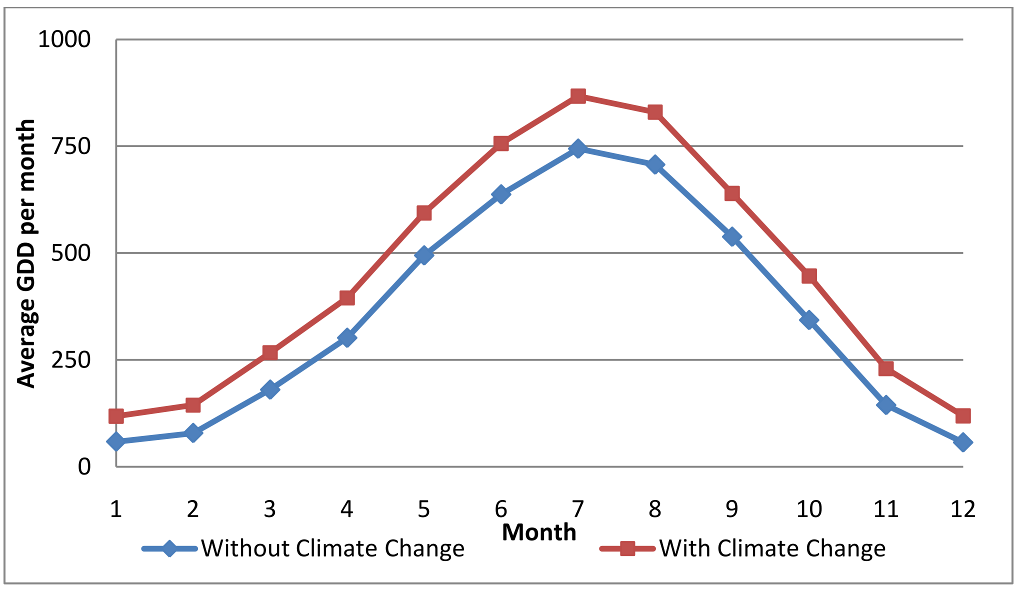

Figure 34: Average growing degree days accumulated each month, under the original case and the climate change scenario. Data for Thomas County, 1985-2010.

Additionally, climate projections say that precipitation will increase in all months of the year except for June, July, and August. The increased precipitation in the early months of the growing season will decrease the amount of irrigation need required. In June, July, and August, precipitation decreases. This would increase the amount of irrigation needed, but faster maturity means that crops spend less time in July and August, so the effects of decreased precipitation are minimized. The smaller irrigation water requirement under the climate change scenario seems to primarily be a result of the shorter growing season.

In this comparison, all parameters except for climate were assumed to remain constant. Under a climate change scenario, the crop varieties, planting dates and practices, and the irrigation practices may change.

Groundwater Levels

Supplementation of WIZARD data with WWC5 Data

As discussed previously, the WIZARD data does not adequately cover the entire state. For water surface elevations of the entire state, the WWC5 drilling logs must be used to supplement the WIZARD data. For the pilot analysis of the target counties, only the WIZARD data will be used. This is because the target counties all overlie the High Plains Aquifer, where the WIZARD wells are concentrated. In this case, the procedure for estimating yearly depth to water will be the same as the procedure using both databases.

Procedure for Calculating Average Water Surface Elevation

Note: The following procedure was performed using the command line in ArcMap. Writing code for ArcMap allowed for the different steps to be performed in batch by using the command prompt. The commands used and the format of the input is supplied in Appendix E.

1. Each database was broken up into sets of measurements by year. Using the "Select" tool in ArcToolbox (Analysis-Extract-Select), the WWC5 and WIZARD databases were broken up into separate layers that only contained measurements in year X. The WIZARD wells did not have an entry for county, so the county was added to the measurements using the "Spatial Join" tool (Analysis-Overlay-Spatial Join).
2. Before the WIZARD_X and WWC5_X tables could be joined, they had to contain the same attributes; each well needed to have the variables for the county, the latitude and longitude, the year of the measurement, the land surface elevation, the source of measurement and the depth. The land surface elevation was pulled from the 7.5 minute National Elevation Dataset. Once all the data was consistent between databases, any extraneous fields were deleted.

3. Finally, the WWC5 and the WIZARD databases were merged for each year using the “Merge” tool (Data Management-General-Merge). It is important that each database has the same variable names and that they are the same data type or else the datasets will not combine correctly.
4. To create a raster of the potentiometric surface (water table) for each year, the data had to be in a projected coordinate system instead of a geographic coordinate system. Because most of the wells are in the southern half of the state, the Kansas State Plane South projection was used. The raster was created the inverse distance weighted method. Kriging, an interpolation method commonly used in groundwater [16-17, 78-80], was not used in this instance because it left several large areas of no data and also predicted several areas where the depth to water was unreasonably different than nearby wells.
5. In order to tabulate the yearly depth to water for each county, the Zonal Statistics as Table (Spatial Analyst-Zonal-Zonal Statistics as Table) tool was used. This calculated the maximum, minimum, mean, and standard deviation of the depth to water for each county. These tables were then exported as DBASE files and imported into Excel.

The average water table elevation for the target counties can be found in Appendix E.

Average Groundwater Levels by County

The yearly average groundwater level for each of the seven target counties was analyzed in conjunction with the annual groundwater withdrawals. These water levels are plotted in Figure 35 through Figure 42. The water surface elevation for a given year is the water surface elevation at the start of that calendar year, the average of all the measurements taken over the prior winter. Some counties, like Finney County in Figure 35 and Stevens County in Figure 36, exhibit a steady, almost linear decline in groundwater elevation as the quantity of groundwater removed stays roughly level. Both of these two counties use significantly more groundwater than any of the other target counties.

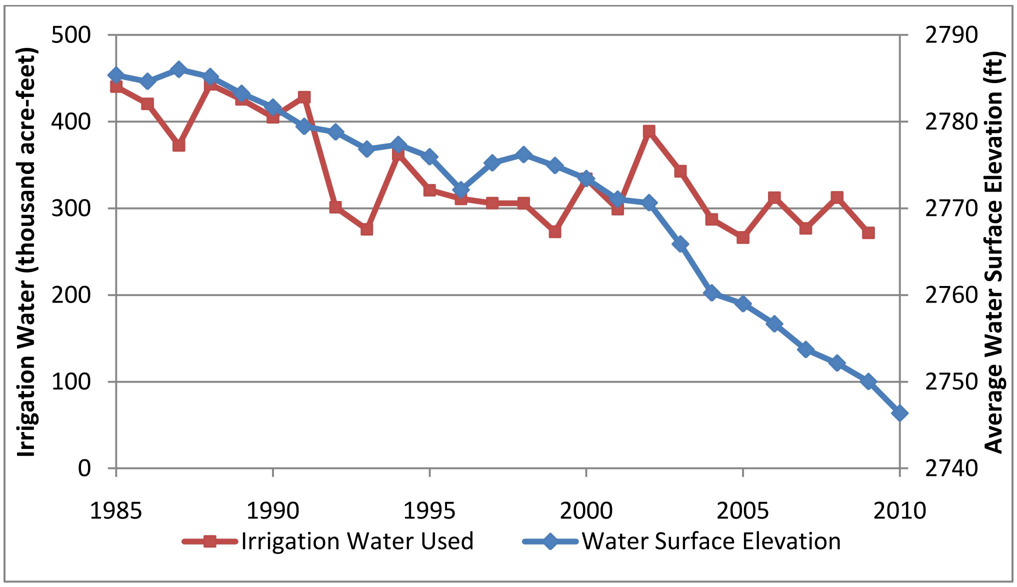

Figure 35: Average water surface elevation for Finney County, 1985 through 2010

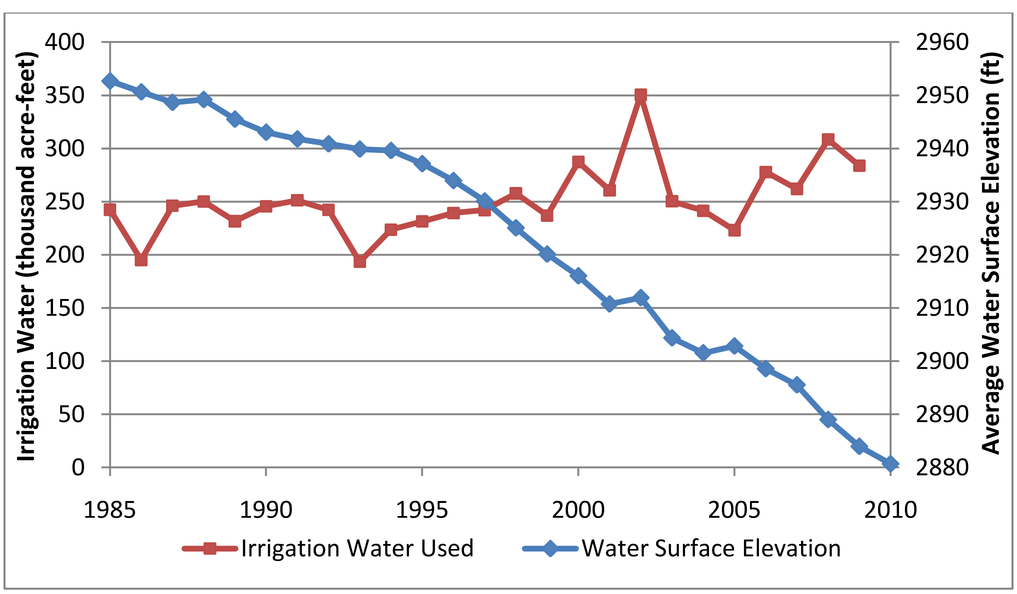

Figure 36: Average water surface elevation for Stevens County, 1985 through 2010

Barton County is significantly different than either Finney or Stevens Counties. The general trend of the water table is up, not down, having risen 10 feet over the last twenty-five years. Additionally, the quantity of water used for irrigation is an order of magnitude less than either Finney or Stevens. As can be seen from Figure 37, Barton County's chart of water used and water surface elevation, the year 1992 marks a large change in both water use and water table. The amount of irrigation water used drops from 50,000 acre-feet in 1991 to 20,000 acre-feet in 1992. That same year, the average water surface elevation rises 4 feet across the county; over the course of the next year, the water table rises another 3 feet.

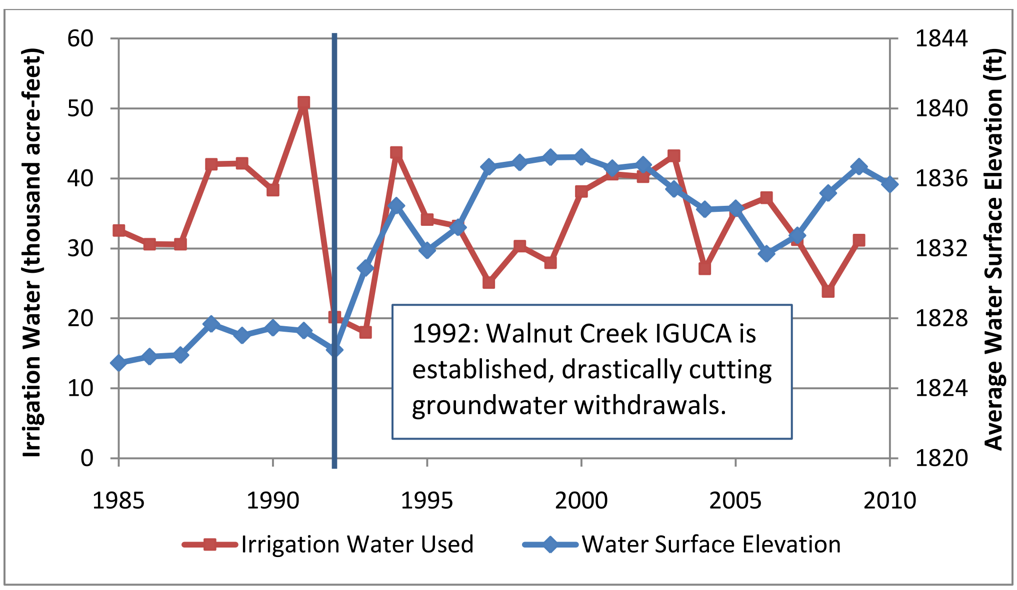

Figure 37: Average water surface elevation for Barton County, 1985 through 2010

In 1992, the Walnut Creek IGUCA was established to maintain water levels in the Cheyenne Bottoms wetlands [33-34], an important site for wildlife, especially migratory birds [81-82]. The Chief Engineer from the Department of Water Resources limited all water rights in the Walnut Creek region depending on if they were assigned before or after October 1, 1965. Water use was cut for the junior water rights (newer than October 1, 1965) by between 64 and 71 percent and for the senior water rights by between 22 and 33 percent [33-34]. This drastic cut in withdrawals is shown in Figure 37 – in 1992, the irrigation withdrawals dropped by over 50%. The water table responded immediately, rising approximately 8 feet between 1992 and 1994.

No IGUCA is currently limiting withdrawals in Stafford County (Figure 38), but water use and levels there are just as variable as they are in Barton County. Water use peaks several times, with each peak associated with a drop in the water table. In 1991, the county-wide water use reaches 110,000 acre-feet and drops the next year; water levels immediately begin to rebound until 1994, when water use jumps again. This is seen again in 2003 and 2008 as water use suddenly drops off while the water table begins to rebound.

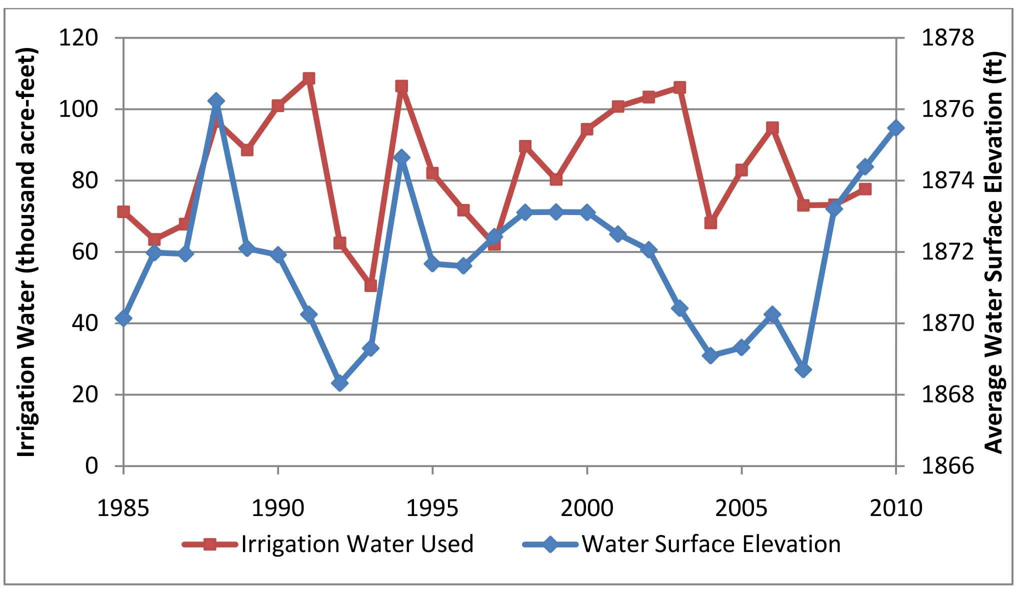

Figure 38: Average water surface elevation for Stafford County, 1985 through 2010

Reno County's water table (Figure 39) also rises and falls throughout the years, beginning 2010 at approximately the same level as it began 1985. In 1991, it exhibits an abrupt drop in withdrawals followed by an increase in the water table, similar to Barton and Stafford Counties. From 1998 to 2003, water use in Reno County is generally increasing. Over this same time period, the water table is in decline. In 2003, however, as record amounts of water are being withdrawn, the water table actually rises almost a foot. In 2006, water use again surpasses 50,000 acre-feet, and the water table drops 2 feet. Over the next few years, the trend reverses: water use declines, and the water table begins to recover again.

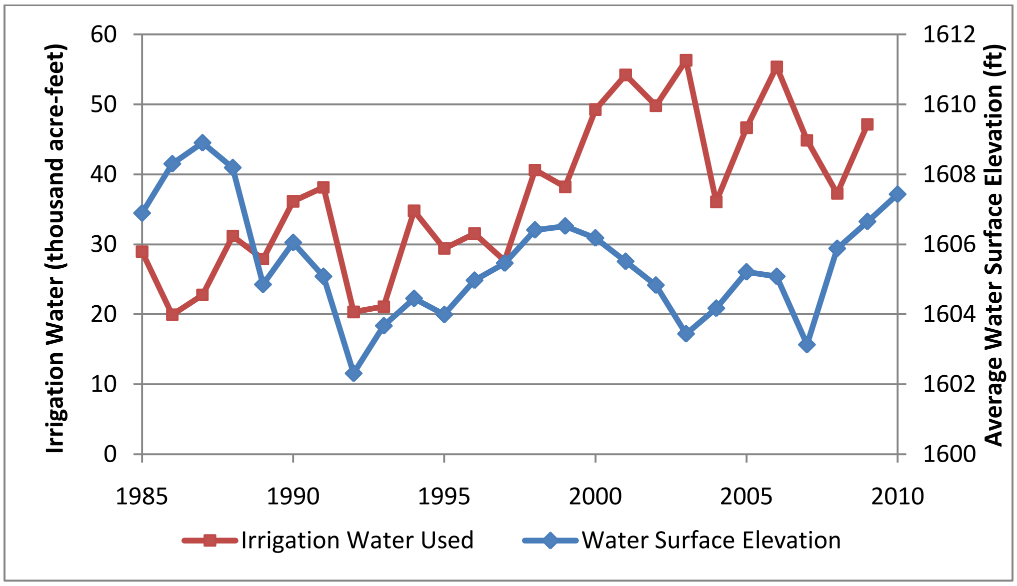

Figure 39: Average water surface elevation for Reno County, 1985 through 2010

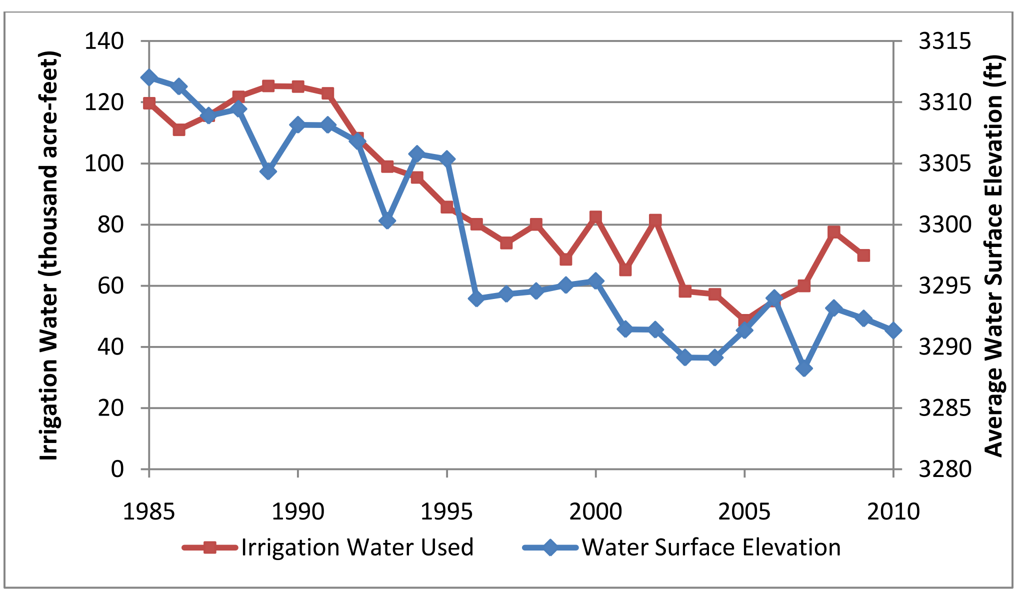

Figure 40: Average water surface elevation for Morton County, 1985 through 2010

Morton County (Figure 40), like Barton and Stevens, has a downward trending water table. Throughout the county, more water is being withdrawn than in Reno or Stafford in the first half of the time period. This could partially explain the downward trend – from 1985 to 1997, the water use ranged from 75,000 to 125,000 acre-feet and the water table fell 17 feet. From 1997 to 2010, water use stayed between 50,000 and 80,000 acre-feet and the water table fell only about 3 feet. There are no sharp peaks or valleys in water use, but the water table does drop 5-10 feet from one year to the next several times; this is probably a result of which wells were measured in each year. In 1989, 37 wells were measured in Morton County compared with 39 in both 1988 and 1990. Moreover, the geographic distribution of wells measured in each year does not significantly change (Figure 41), but there is a pocket in the southwest corner of the county that is filled by the 1989 measurements. Wells in this location could be close enough to be influenced by the Cimarron River, but that would imply a higher water table in 1989 instead of a lower water table. The Kansas Geological Survey has noted several instances where repeat measurements on a well in the same year occasionally result in a difference of 5-10 feet, with one rise of 30 feet being noted as erroneous [17]. It is possible that some of the years where the water table drops several feet only to jump back up for the next year are the result of measurement error and noise.

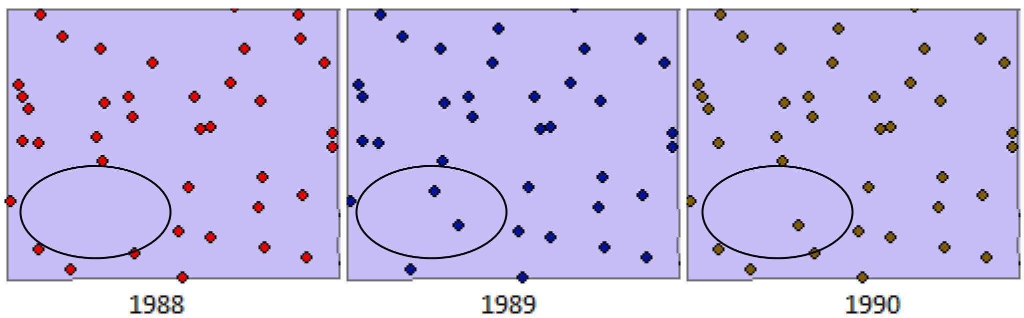

Figure 41: Distribution of measured wells in Morton County, 1988-1990

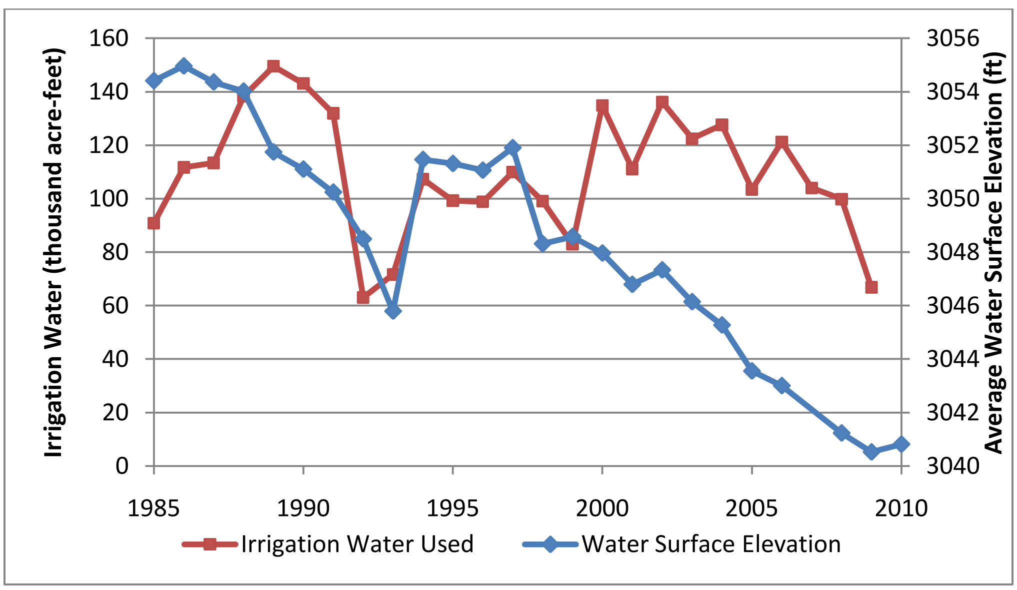

Figure 42: Average water surface elevation for Thomas County, 1985 through 2010

Thomas County (Figure 42) is remarkably similar to Morton County. Both counties exhibit a general downward trend in water surface elevation that overshadows the year-to-year changes, and both counties tend to have annual withdrawals in the middle range of the counties examined in terms of water use. There is one significant valley in both the water use and the water surface elevation graph. Beginning in 1989, the county's water use begins to drop. The water use bottoms out in 1992, but the rebound in the water surface elevation is lagged by a year; the water table drops an additional 2 feet despite the dramatic decrease in consumption. In 1993, the water table rises by 5 feet even though withdrawals jump from 70,000 to 110,000 acre-feet. Following 1993, the water surface elevation gradually begins to drop again linearly while withdrawals hover between 80,000 and 140,000 acre-feet. The one remaining drastic jump in water use, from 1999 to 2000, does not affect the water table any differently than the neighboring years. The decreases in water use in 2001 and 2009, however, are observed in the water table – the average water surface elevation increases in both years after falling in the preceding years with higher consumption.

Discussion of Results

Accuracy of the Water Budget Model

The water budget model with scheduled irrigation based on soil moisture predicted water-use well compared to reported water-use (a slope of 1.015 and r^2 of 0.906). However, there are several possibilities for the slight variation between the estimated need and reported use.

The water budget model is using a county-wide average value for water holding capacity in the top 100 cm of soil. This could be improved by changing the depth of the soil column that is used to calculate water holding capacity based on average rooting depth for the different crops over the growing season [83-85]. Additionally, this model pulls information from many different data sources. County-level irrigated acreage was retrieved from the National Agricultural Statistics Survey, and some data are missing. These data were filled in by using the Census of Agriculture (available every five years) and by analyzing trends in the number of irrigated acres by crop in each county. Due to the discrepancies between the two sources, it is likely that even when a value is reported, it is not completely accurate.

Weather data were retrieved in all cases from a single station for each county. This approach assumes that the weather at that point is valid across the entire county; in some cases, such as in Thomas County, the weather station is located in the center of the county, but in Morton County, the weather station is located on the very southern edge of the county. Additionally, some counties do not have weather data available for this range of years. The water budget for Barton County is using a weather station from nearby Pawnee County, and Stevens County uses the weather data from nearby Morton County. Various data quality issues have also been raised about the weather data (personal communication with Dr. Johannes Feddema): one station’s record includes a day in January where the high was 40°C. This location has weather records from both the HPRCC and the long range weather stations, and the 40° day is present in only one record. Discrepancies between the two data sources indicate the possibility of equipment error or malfunction in one or both records.

The WIMAS database has uncertainty in it as well. While the completed water use forms go through quality control through the Kansas Department of Water Resources, quality assurance has only been performed since 1990 [35]. It wasn’t until 1983 that water use forms were even required and the late 1980s that users who failed to report their water use were fined [34-35, 86]. Automated water meters were made mandatory for new points of diversion across the state in 1987 [87]. Individual groundwater management districts had powers to enact additional requirements: GMD 3 established a policy requiring all large capacity wells to install flow meters from 1993 through 1996 [88]. All five of the groundwater management districts currently require flow meters on nearly all wells [87]. Early measurements of water quantity in the WIMAS database are, for this reason, theoretically less trustworthy than more recent measurements. It is unclear if this is a large contributor to error, though. Figure 43 shows the error between the model’s predicted water need and the reported water use for irrigation over time. Error in the model is relatively flat from the beginning of the time period through 2000, when the error begins to shift upward. This could be a result of the adoption of water meters providing a more accurate knowledge of how much water is being used. Social factors such as increased education and concern about groundwater quantity or the spread of conservation plans could also affect how much water is being withdrawn.

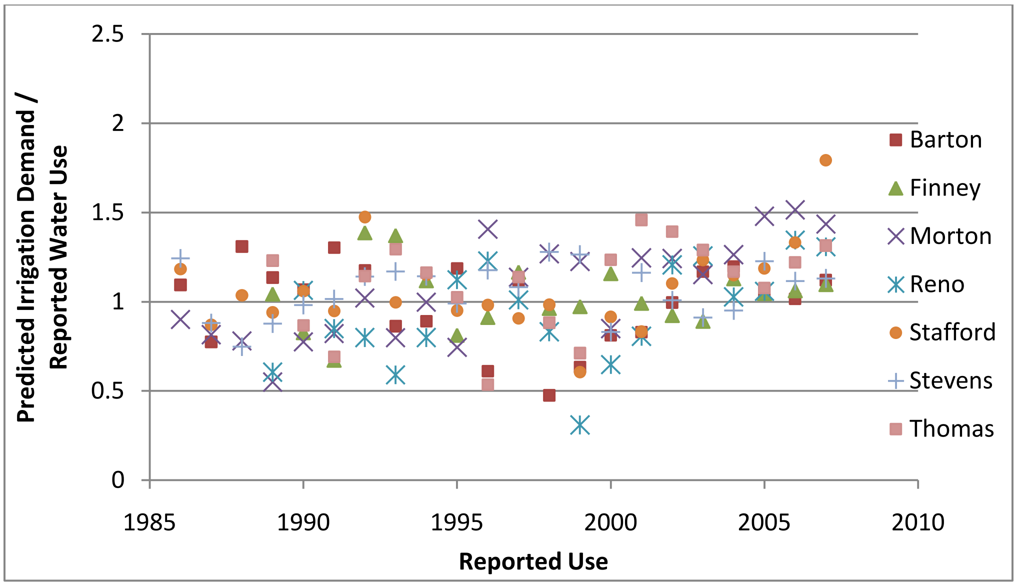

Figure 43: Comparison of predicted use to reported use over time

Even if all the data used in the model were accurate, there are still sources for error between the model and reality. Under Kansas water law, if the owner does not use his entire water right for five years without "due and sufficient cause," then the state is able to seize that right [89]. This law is often misunderstood [89], which can lead to a farmer using his entire water right every year even if he could limit his irrigation with no adverse effects. Having adequate moisture is one of the several qualifications that excuse the underuse of a water right.

The Walnut Creek IGUCA is currently the only IGUCA that has restricted withdrawals, but most of the other IGUCAs are closed to new water rights [32-34, 90-95]. When water rights affected by this IGUCA were limited, the water table responded immediately (Figure 37). This rise was not temporary; even though withdrawals have risen slightly since 1992, the water table has risen over 8 feet across Barton County. Restrictions in other IGUCAs could have similar results, and if conservation plans limited withdrawals over a larger area, recharge to the aquifer could begin to reverse some of the severe depletion that has happened throughout the High Plains Aquifer.

Despite the uncertainty involved in the data and the human factor involved in deciding when to irrigate, the irrigation model is able to reasonably predict irrigation on a county scale. Because the predicted irrigation use correlates well with the actual irrigation use, it will be possible to model how irrigation may be practiced under different climate change scenarios. IPCC projections of precipitation and temperature could be applied to the weather records, and the irrigated area in each county could be informed by potential conservation plans and economic models.

Groundwater Levels

The seven target counties fall into three general categories of water use. Finney and Stevens Counties are in the highest tier, with between 200,000 and 400,000 acre-feet used annually. Barton and Reno both use less than 60,000 acre-feet annually, even in the high years. The remaining three counties, Morton, Stafford, and Thomas, all fall between these two ranges. As can be seen in Table 12, four of the seven target counties experienced a decline in water surface elevation of the 25 years analyzed. These four counties were also the four counties with the highest average water use. The three counties with the lowest water use all either experienced a rise in the water table or no change over the time period.

Table 12: Average water use and change in water surface elevation by county, 1985 - 2010

County	Average annual irrigation use (acre-feet)	Average annual change in water surface elevation (ft)
Finney	340,000 ± 59,000	-1.56 ± 1.89
Stevens	250,000 ± 33,000	-2.88 ± 2.28
Thomas	110,000 ± 23,000	-0.53 ± 1.85
Morton	88,000 ± 25,000	-0.83 ± 3.69
Stafford	83,000 ± 17,000	0.21 ± 2.19
Reno	37,000 ± 11,000	0.02 ± 1.38
Barton	34,000 ± 8,000	0.41 ± 1.79

The target counties behave differently on a year-to-year basis depending on how much water is withdrawn. The highest rates of withdrawal tend to match up with a regularly declining water table that is minimally impacted by variations in the amount of irrigation. The lowest tier of counties tend to have a water table that is impacted by variation in water use but did not lower significantly over the 25 years examined. The remaining three counties, where water use is generally higher than 60,000 acre-feet but lower than 150,000, exhibit a mixed reaction. Trends in the water surface elevation are generally downward in Morton and Thomas, but Stafford County ends the time period at approximately the same elevation that it started at. These three counties all have some sharp jumps and drops in the water table, but not as many (or as drastic) as the counties in the lowest tier of water use. Additionally, Barton, Reno, and Stafford Counties all overlie the eastern part of the High Plains Aquifer and have potential rates of recharge of between 1 and 3 inches per year [12]. These three counties all experienced an average increase in water table elevation during the study period. Morton, Stevens, Finney, and Thomas Counties, which all experienced declines in the water table, have potential recharge rates of less than an inch per year [12]. This lower rate of recharge, combined with the higher average withdrawals, may have contributed to the decline of the water table in these counties.

As can be seen in Figure 44 and Figure 45, Barton and Stafford Counties, both on the low end of irrigation withdrawals, have water tables that are responsive to a change in irrigation use. Other counties are not so responsive: Finney County (Figure 46) and Morton County (Figure 47), both exhibit no correlation between water use and the change in water table elevation. This difference may be partially explained by geography. Barton and Stafford Counties are adjacent, while Finney and Morton Counties are in the southwest part of the state, where the heaviest depletion of the aquifer has occurred. The strength of the relationship between withdrawals and depletion is probably not completely dependent on the magnitude of the withdrawals at each county as well – Stafford County and Morton County both withdraw similar amounts of water each year, but the response of the aquifer to those withdrawals is vastly different in each county.

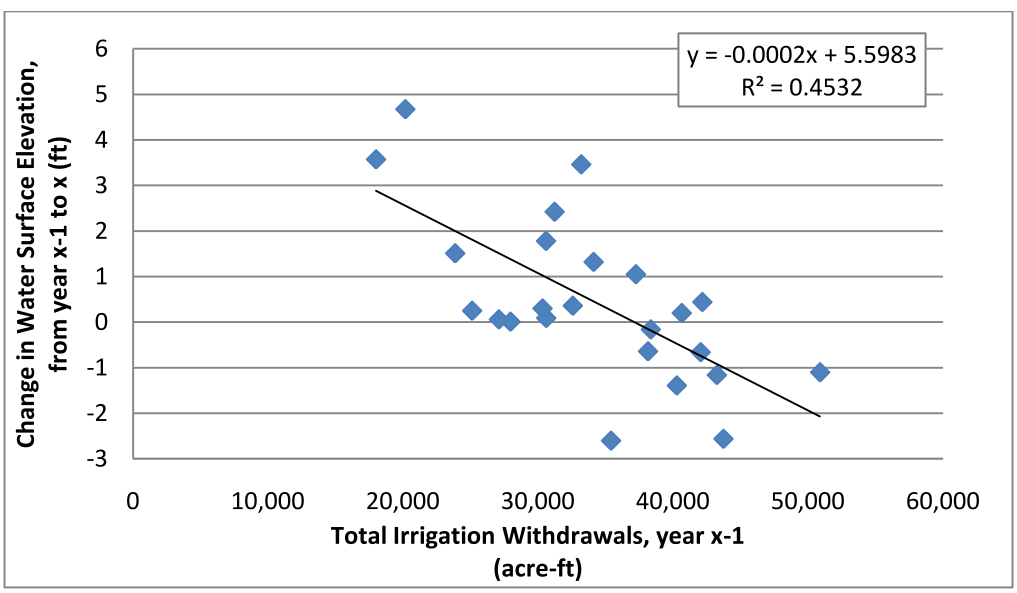

Figure 44: Annual change in water surface elevation versus annual irrigation withdrawals for Barton County, 1985-2007

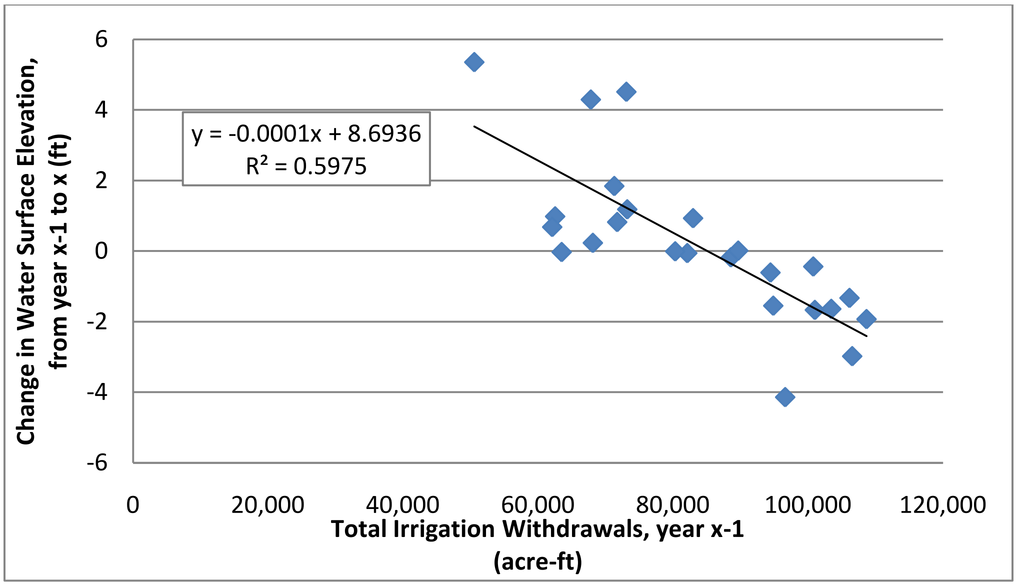

Figure 45: Annual change in water surface elevation versus annual irrigation withdrawals for Stafford County, 1985-2007

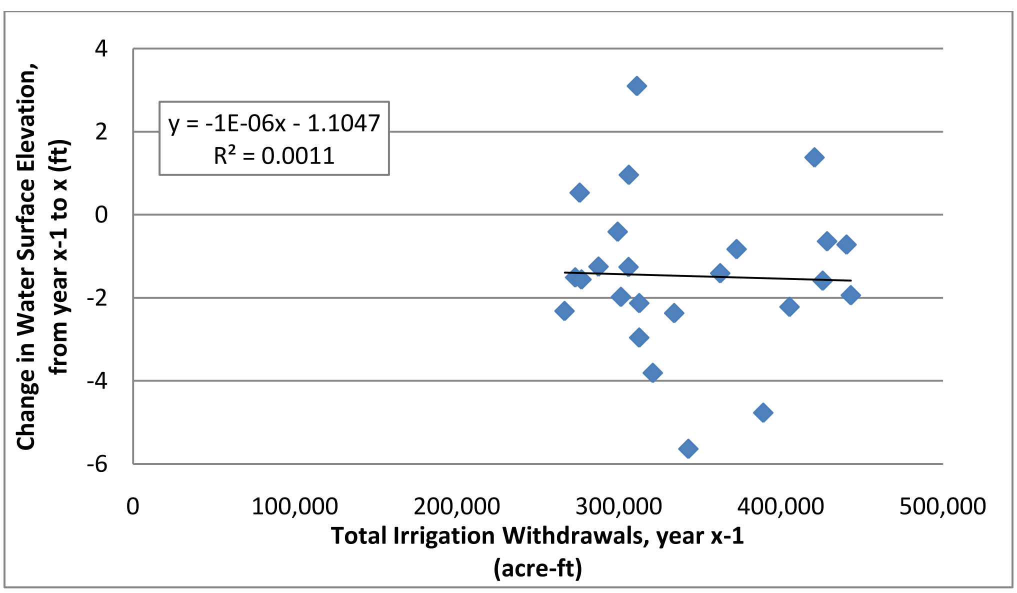

Figure 46: Annual change in water surface elevation versus annual irrigation withdrawals for Finney County, 1985-2007

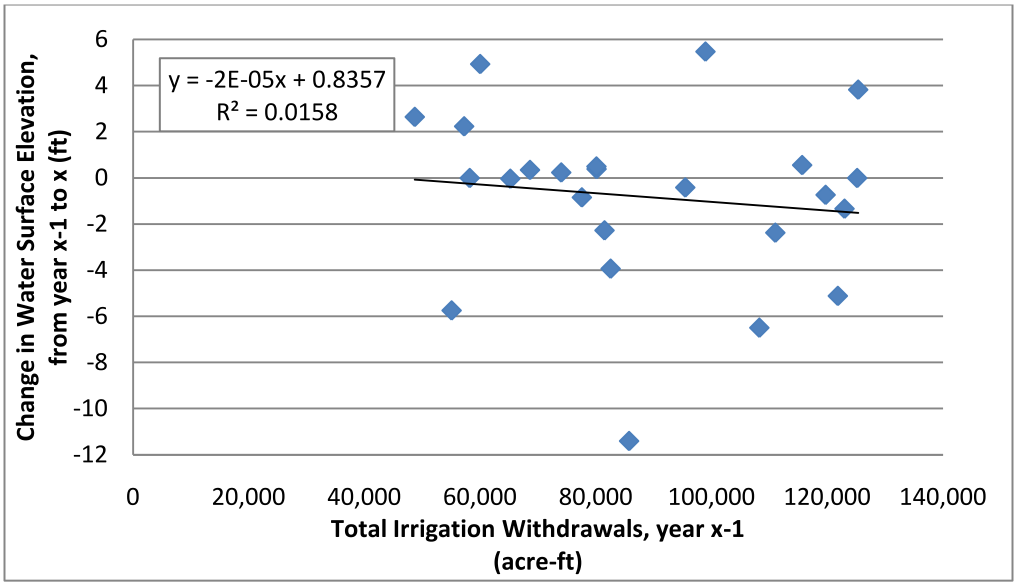

Figure 47: Annual change in water surface elevation versus annual irrigation withdrawals for Morton County, 1985-2007

Conclusions

The use of a water budget model allows for the prediction of irrigation water use based on land use and climate. Daily evapotranspiration was calculated using the Hargreaves-Samani evapotranspiration model method scaled using growing-degree day crop coefficients. Scheduled irrigation was modeled to maintain adequate soil moisture throughout the growing season. The depth of irrigation water applied was then multiplied by the irrigated acreage of each crop in each of the target counties to determine the irrigation need by county. This calculated irrigation need was compared to historic reported water use; the model matched the county level predicted water use with the reported use with a slope of 1.015. While the relationships hold with water use aggregated to the county level, it remains to be seen if irrigation demand can be predicted on a finer scale.

The relationship between withdrawals and drawdown of the water table needs to be further investigated. A qualitative analysis of the yearly groundwater levels for the seven target counties revealed that the water table is sensitive to variations in water use in some locations. The counties with highest water use (Finney and Stevens) tended to have a water table that was constantly in decline, regardless of changes in the amount of water withdrawn from the aquifer. On the other hand, counties such as Barton or Reno County tend to have a water table that is much more responsive to changes in water use. When the water use increases, the water table tends to go down, but when use starts to drop, then the water table begins to rise again. This is seen most clearly in 1992 in Barton County, when the Walnut Creek IGUCA went into effect.

Any relationship between drawdown in the water table and irrigation withdrawals at the county scale will have to be more than just a linear regression. Even in Stafford County, where the correlation was the best, the R^2 was less than 0.6. It is possible, however, that a correlation can be determined at a local level, perhaps comparing water use density to the change in water level [17].

While the water budget model works on a county-level scale, it is uncertain whether the approach will be equally valid when a field-level scale is implemented. More investigation needs to be performed on Kansas water rights to find out the viability of linking withdrawals to a place of use. Then, the nature of the impact of withdrawals on the High Plains Aquifer needs to be examined. This affect can then be modeled in order to complete link between climate, land use, and groundwater availability in the High Plains Aquifer.

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Appendix A: Metadata file for WIMAS database

This file was received from the Kansas Department of Water Resources in response to an open records request in December 2010 by Matt Hiatt. It accompanied a Microsoft Access database of water rights from the WIMAS database. Any codes that reference attached files (“attached basin table” or “WaterUseReportCodes.doc”) can defined in the WIMAS User Manual, located at http://hercules.kgs.ku.edu/geohydro/ofr/2005_30/wimas_ofr2005_30_manual.htm. DWR’s supplied metadata follows:

This dataset represents water use during the years 1985 - 2009. Water right information is spatially referenced by where water is diverted from its original source referred to as Points of Diversion (PD). Information locating and attributing water use data for the PDs are retrieved via Structured Query Language (SQL) queries to DWR's ORACLE RDMS based Water Rights Information System (WRIS).

Individual PDs containing more than one water right or use made of water are "stacked" in the sense that the point representing the PD will be plotted to the same geographic coordinates for every unique water right, use made of water, or water use year associated with it. Water use records are not considered "publishable" until the 1987 water use year.

When conducting summary routines on total acre feet used or acres irrigated on this dataset, the primary key for water use must be honored to avoid duplicating data. The primary key for water use consists of WR_ID, UMW_CODE, PDIV_ID, WUAPERS_ID, WUACOR_NUM, WUA_YEAR, and FO_NUM. These fields have to be unique for proper summary routines.

No formal testing on this dataset is conducted. The dataset creation is an automatic process that retrieves data from information stored in ORACLE RDMS. Any errors in the original ORACLE tables will be represented in this dataset.

The Kansas Department of Agriculture, Division of Water Resources exercises great care in the creation and analysis of its data sets. However, the Kansas Department of Agriculture, Division of Water Resources offers no warranty or guarantees of the accuracy or completeness of the data and assumes no liability for errors of this kind. The digital data is offered on "as is" basis with the user assuming all risk.

RIGHT_TYPE: Right type identifies the type of water right.
A = Appropriation; B = Basin Term; D = Domestic; P = Temporary; T = Term; V = Vested
VCNTY_CODE: County abbreviation the vested right is located in. County abbreviations are the same as used on Kansas license plates.
WR_NUM: A sequential priority number assigned to each right as water right applications are received by KDA-DWR. Each water right has a unique number. The lower the number, the more senior the right.
WR_QUAL: A water right qualifier is used if a water right has been divided for administrative purposes.
WR_ID: Unique computer assigned identification number for a water right.
FO_NUM: DWR field office number the PD is located in.
1 = Topeka, 2 = Stafford, 3 = Stockton, 4 = Garden City
BASIN: DWR assigned basin number the PD is located in. See attached basin table (basin).
STREAM: DWR assigned stream number for surface PDs. See attached stream table (stream).
SOURCE: Water source from which the PD is diverting from.
S = Surface, G = Ground
AQUIFER: A code for the aquifer unit the groundwater PD is accessing. See attached aquifer table (aquifer).
GWMD_NUM: Number of the Groundwater Management District the PD is located in.
1 = Western Kansas GMD #1, 2 = Equus Beds GMD #2, 3 = Southwest Kansas GMD #3,
4 = Northwest GMD #4, 5 = Big Bend GMD #5
SUA_NAME: Special Use Area the PD is located in.
CNTY_NAME: County abbreviation the PD is located in. County abbreviations are the same as used on Kansas license plates.

WRF_STATUS: Status of the water right. See attached status code table (status).
UMW_CODE: Use made of water code for the water right. An individual water right may have multiple uses of water.

ART = Artificial Recharge
CON = Contamination Remediation
DEW = Dewatering
DOM = Domestic (private)
FPR = Fire Protection
HYD = Hydraulic Dredging
IND = Industrial
IRR = Irrigation
MUN = Municipal
REC = Recreation
SED = Sediment Storage
STK = Stockwatering
THX = Thermal Exchange
WTR = Water Power

PDIV_ID: Unique computer assigned identification number for a PD. Each PD has an assigned number.
TWP: Public Land Survey System township number. 1 to 35 townships numbers in Kansas
TWP_DIR
S = South, N = North
RNG: Public Land Survey System range number. 1 to 43 range numbers in Kansas
RNG_DIR: Public Land Survey System range direction.
E = East, W = West
SECT: Public Land Survey System section number. 1 to 36 sections in a township.
DWR_ID: A unique number in each PLSS section assigned to individual PDs.
FEET_NORTH: Feet distance north from the SE corner of the section the PD is located in. Generally 1 to 5280
FEET_WEST: Feet distance west from the SE corner of the section the PD is located in. Generally 1 to 5280
QUAL_FOUR: The fourth and smallest subsection qualifier of a section the PD is located in. Given the example of CW W2 SE SW, the QUAL_FOUR value would be CW.
QUAL_THREE: The third subsection qualifier of a section the PD is located in. Given the example of CW W2 SE SW, the QUAL_THREE value would be W2.
QUAL_TWO: The second subsection qualifier of a section the PD is located in. Given the example of CW W2 SE SW, the QUAL_TWO value would be SE.
QUAL_ONE: The first and largest subsection qualifier of a section the PD is located in. Given the example of CW W2 SE SW, the QUAL_ONE value would be SW.
NUM_WELL: Number of wells in a battery.

WUAPERS_ID: Computer assigned unique identification number for a legal person.
WUACOR_NUM: Computer assigned unique identification number for a correspondent.
WUA_YEAR: Water use year accessed from WRIS.
HOURS_PUMP: Reported total annual hours pumped for the water use year.
PUMP_RATE: Reported average annual pumping rate for the water use year. Numeric values in gallons per minute.
METER_QTY: Reported total annual metered quantity for the water use year.
METER_UNIT: Code for the units the metered quantity is reported in. Available for 1996 to present reports. For water use before 1996, WUR_CODE (in some cases) can used to determine the meter unit. See attached file WaterUseReportCodes.doc.
WUR_CODE: DWR assigned water use report code. See attached file WaterUseReportCodes.doc.
ACRES_IRR: Reported acres irrigated during the water use year.
DATE_MEASR: Reported date the PD's groundwater level was measured.
DPTH_WATER: Reported depth to the water table in feet.
DPTH_WELL: Reported depth of the well in feet.
REEL: DWR micro-film reel number.
BLIP: DWR micro-film blip number.
RPT_DATE: Date the water use report was received by DWR. Effective with 1989 reports.
CHEM_IND: Chemigication indicator from water use report. Effective with 1990 reports.
Y = Chemigated during the water use year, N = No chemigation conducted.
CROP_CODE: Reported type of crop irrigated for the water use year. Effective with 1990 reports. See attached file WaterUseReportCodes.doc.
SYSTEM: Type of irrigation system. Effective with 1991 reports. See attached file WaterUseReportCodes.doc.
EMETER_R: Reported ending meter reading for the water use year. Effective with 1994 reports.
AF_USED: Total annual acre-feet of water used for the water use year. This item is calculated by DWR depending on information provided in the Water Use Report.
LATITUDE: Geographic latitude coordinate of the PD. This item is provided either by GPS measurement, calculated from PLSS descriptions using the Kansas Geological Survey's LEO III conversion software, or calculated by DWR. If more than one coordinate value exists, the GPS value is chosen followed by LEO and DWR's calculation. NAD 27 Datum.
LONGITUDE: Geographic longitude coordinate of the PD. This item is provided either by GPS measurement, calculated from PLSS descriptions using the Kansas Geological Survey's LEO III conversion software, or calculated by DWR. If more than one coordinate value exists, the GPS value is chosen followed by LEO and DWR's calculation. NAD 27 Datum.

Appendix B: Irrigated areas for each county

The following tables show the irrigated area in acres for corn, sorghum, soybeans, and wheat for each of the target counties. Data was retrieved from the National Agricultural Statistics Service Quickstats 1.0 and the Census of Agriculture's Farm and Ranch Irrigation Survey. Any data that was missing from NASS was interpreted based on trends of surrounding years and reported data from the Ag. Census. This interpreted data is shown italicized and red.

Barton County

	NASS Quickstats				Census of Agriculture				Total Irrigated Areas	
	Corn	Sorghum	Soybeans	Wheat	Corn	Sorghum	Soybeans	Wheat	Ag Census	NASS QS
1985	8,700	12,200	5,600	6,400						32,900
1986	12,000	10,900	4,900	5,400						33,200
1987	10,200	13,200	6,000	5,900	9,382	7,967	5,239	3,859	26,447	35,300
1988	11,400	15,700	10,000	7,000						44,100
1989	14,700	12,100	9,500	7,700						44,000
1990	17,100	8,500	10,100	6,900						42,600
1991	20,000	6,400	8,000	9,000						43,400
1992	19,400	6,700	5,400	5,100	21,533	5,263	5,666	3,094	35,556	36,600
1993	20,600	3,400	6,600	3,100						33,700
1994	22,900	5,500	7,600	2,500						38,500
1995	23,400	5,200	8,300	3,000						39,900
1996	24,200	5,600	6,700	1,800						38,300
1997	26,000	4,700	9,800	*500*	25,283	3,871	9,617	743	39,514	41,000
1998	18,800	*2,000*	6,800	*500*						28,100
1999	19,300	*2,000*	11,500	*1,000*						33,800
2000	18,100	*2,000*	14,400	*1,000*						35,500
2001	22,800	3,200	12,000	*2,000*						40,000
2002	21,400	4,900	10,000	*2,000*	21,904	3,678	9,495	2,497	37,574	38,300
2003	18,800	3,500	10,500	*2,000*						34,800
2004	17,800	3,700	*8,000*	*4,000*						33,500
2005	19,000	*2,000*	9,700	*4,000*						34,700
2006	17,100	4,100	12,300	6,700						40,200
2007	23,700	2,500	8,500	5,200	20,715	2,309	7,761	5,430	36,215	39,900

Finney County

	NASS Quickstats				Census of Agriculture				Total Irrigated Areas	
	Corn	Sorghum	Soybeans	Wheat	Corn	Sorghum	Soybeans	Wheat	Ag Census	NASS QS
1985	39,200	34,900	8,400	80,100						162,600
1986	38,400	29,300	10,900	65,400						144,000
1987	47,300	32,700	9,100	63,000	49,215	28,229	7,773	61,592	146,809	152,100
1988	47,800	25,000	13,400	59,600						145,800
1989	56,400	31,900	13,100	60,000						161,400
1990	57,800	27,300	13,600	77,500						176,200
1991	66,700	27,700	16,800	70,000						181,200
1992	72,900	22,300	13,300	83,600	69,250	23,853	12,723	71,960	177,786	192,100
1993	68,600	14,700	11,400	72,000						166,700
1994	75,700	14,400	9,400	72,300						171,800
1995	84,500	15,300	7,400	54,700						161,900
1996	*90,000*	13,000	6,200	53,900						163,100
1997	96,500	11,200	6,000	57,000	97,303	10,713	5,581	54,576	168,173	170,700
1998	90,800	7,000	6,700	55,000						159,500
1999	96,900	6,800	*8,500*	52,500						164,700
2000	92,000	4,400	*11,000*	52,100						159,500
2001	70,300	7,100	*13,400*	40,900						131,700
2002	64,800	12,700	14,500	41,800	74,590	11,896	14,508	37,265	138,259	133,800
2003	*67,000*	13,700	15,900	46,500						143,100
2004	*68,000*	10,500	*13,000*	47,900						139,400
2005	70,000	9,300	*10,000*	55,300						144,600
2006	54,300	9,400	*8,000*	54,200						125,900
2007	83,200	6,600	6,000	51,800	78,472	6,722	6,062	40,856	132,112	147,600

Morton County

	NASS Quickstats				Census of Agriculture				Total Irrigated Areas	
	Corn	Sorghum	Soybeans	Wheat	Corn	Sorghum	Soybeans	Wheat	Ag Census	NASS QS
1985	3,900	22,500	800	30,200						57,400
1986	4,700	19,700	700	22,800						47,900
1987	2,600	26,000	300	19,000	2,475	13,856	(D)	17,937	34,268	47,900
1988	700	13,800	400	20,700						35,600
1989	4,000	17,900	100	16,000						38,000
1990	5,600	13,500	100	22,000						41,200
1991	7,700	16,000	*200*	21,500						45,400
1992	10,500	9,800	*200*	22,500	6,967	10,099	–	19,364	36,430	43,000
1993	11,700	6,400	*200*	20,500						38,800
1994	11,600	8,800	*200*	21,600						42,200
1995	11,400	9,500	*200*	13,900						35,000

1996	*13,000*	7,600	600	20,900						42,100
1997	14,900	7,500	400	22,200	14,849	6,382	–	15,778	37,009	45,000
1998	18,600	4,100	200	20,500						43,400
1999	19,400	4,700	*200*	20,200						44,500
2000	22,800	3,600	*200*	13,500						40,100
2001	13,000	4,800	*200*	17,900						35,900
2002	15,200	4,900	200	15,800	11,897	7,475	–	14,159	33,531	36,100
2003	*18,000*	4,400	*200*	13,800						36,400
2004	*21,000*	5,400	*200*	15,200						41,800
2005	23,500	5,100	*200*	13,900						42,700
2006	14,800	4,700	*200*	14,700						34,400
2007	18,900	3,000	*200*	17,700	25,319	5,950	–	16,798	48,067	39,800

Reno County

	NASS Quickstats				Census of Agriculture				Total Irrigated Areas	
	Corn	Sorghum	Soybeans	Wheat	Corn	Sorghum	Soybeans	Wheat	Ag Census	NASS QS
1985	4,600	16,300	4,100	3,500						28,500
1986	4,900	11,600	4,400	3,300						24,200
1987	7,400	2,800	5,400	3,100	8,847	7,851	3,905	2,999	23,602	18,700
1988	8,200	7,200	6,800	2,300						24,500
1989	6,800	8,000	5,600	2,000						22,400
1990	11,500	8,000	5,100	3,400						28,000
1991	11,800	5,900	6,400	2,900						27,000
1992	10,400	6,200	5,400	2,600	11,438	4,874	5,034	3,843	25,189	24,600
1993	9,300	4,600	5,700	2,700						22,300
1994	11,000	5,700	7,500	3,800						28,000
1995	10,900	5,900	7,300	5,600						29,700
1996	11,500	7,500	7,000	5,800						31,800
1997	12,300	4,500	8,000	5,300	10,738	3,975	7,484	2,901	25,098	30,100
1998	13,300	*3,000*	13,900	4,800						35,000
1999	10,800	*2,500*	8,500	4,900						26,700
2000	13,400	*2,000*	13,000	5,300						33,700
2001	15,900	2,200	15,400	4,200						37,700
2002	18,300	4,100	13,100	8,800	17,565	2,994	13,824	6,414	40,797	44,300
2003	22,500	6,200	11,900	13,100						53,700
2004	15,800	4,800	16,200	8,000						44,800
2005	23,600	4,600	14,300	6,500						49,000
2006	19,000	3,300	16,500	12,000						50,800
2007	22,300	4,100	12,700	13,700	20,715	3,336	10,185	7,930	42,166	52,800

Stafford County

	NASS Quickstats				Census of Agriculture				Total Irrigated Areas	
	Corn	Sorghum	Soybeans	Wheat	Corn	Sorghum	Soybeans	Wheat	Ag Census	NASS QS
1985	19,400	22,800	13,900	25,900						82,000
1986	30,300	15,400	15,200	13,600						74,500
1987	29,900	12,900	8,500	11,600	29,140	11,350	7,390	11,272	59,152	62,900
1988	28,600	9,500	12,600	14,200						64,900
1989	26,000	11,500	14,400	12,600						64,500
1990	30,100	9,400	15,400	17,500						72,400
1991	34,100	7,400	13,900	16,300						71,700
1992	36,800	8,400	11,200	19,400	39,876	6,674	9,885	16,187	72,622	75,800
1993	39,500	4,700	11,500	15,500						71,200
1994	45,300	5,400	11,700	14,700						77,100
1995	44,400	5,100	10,200	11,500						71,200
1996	43,300	8,700	10,700	6,700						69,400
1997	41,700	3,500	12,900	11,400	42,895	1,487	12,072	7,975	64,429	69,500
1998	46,300	*3,000*	15,900	10,300						75,500
1999	39,200	*3,000*	15,400	10,800						68,400
2000	44,400	*3,000*	17,000	9,200						73,600
2001	43,500	2,500	12,000	7,900						65,900
2002	45,300	1,800	18,800	9,800	51,231	1,304	12,357	5,055	69,947	75,700
2003	42,300	3,800	19,100	11,700						76,900
2004	37,400	4,000	24,900	15,300						81,600
2005	40,600	3,500	21,500	13,600						79,200
2006	40,800	3,700	21,200	16,500						82,200
2007	45,600	4,700	16,000	22,700	59,866	4,345	16,831	20,223	101,265	89,000

Stevens County

	NASS Quickstats				Census of Agriculture				Total Irrigated Areas	
	Corn	Sorghum	Soybeans	Wheat	Corn	Sorghum	Soybeans	Wheat	Ag Census	NASS QS
1985	17,000	69,000	3,500	47,600						137,100
1986	16,700	41,200	2,600	51,800						112,300
1987	20,200	26,400	1,200	44,700	25,408	35,128	745	48,869	110,150	92,500
1988	21,900	30,700	3,200	31,400						87,200
1989	26,000	33,600	1,200	47,100						107,900
1990	37,800	23,000	1,100	51,000						112,900
1991	47,800	18,500	1,000	54,000						121,300
1992	55,300	15,700	400	49,000	56,803	14,607	438	49,882	121,730	120,400
1993	61,400	8,200	300	49,600						119,500
1994	63,900	9,700	100	45,500						119,200

1995	69,300	8,900	400	43,700						122,300
1996	*70,000*	13,600	700	46,700						131,000
1997	93,500	12,000	400	49,200	95,325	10,681		44,301	150,307	155,100
1998	93,700	10,100	900	50,500						155,200
1999	102,800	9,900	*1,000*	49,200						162,900
2000	104,500	4,100	*2,000*	38,300						148,900
2001	101,000	7,800	3,200	43,300						155,300
2002	91,500	8,800	*4,000*	35,700	96,786	12,508	4,430	33,717	147,441	140,000
2003	*90,000*	12,300	*4,000*	38,200						144,500
2004	102,200	12,500	*4,000*	38,600						157,300
2005	118,400	4,800	*4,000*	38,000						165,200
2006	90,300	11,700	*4,000*	39,600						145,600
2007	103,200	9,600	*4,000*	40,900	114,014	7,002	6,221	33,717	160,954	157,700

Thomas County

	NASS Quickstats				Census of Agriculture				Total Irrigated Areas	
	Corn	Sorghum	Soybeans	Wheat	Corn	Sorghum	Soybeans	Wheat	Ag Census	NASS QS
1985	36,000	30,000	8,300	22,300						96,600
1986	50,200	24,700	8,900	21,000						104,800
1987	46,700	10,000	4,400	19,500	45,449	8,268	3,710	9,745	67,172	80,600
1988	42,400	6,100	6,300	10,000						64,800
1989	51,400	8,900	5,100	13,200						78,600
1990	48,200	5,500	4,700	22,800						81,200
1991	57,700	4,400	4,000	12,600						78,700
1992	50,600	5,100	5,300	7,000	52,414	11,208	6,011	9,767	79,400	68,000
1993	60,200	3,500	3,500	9,800						77,000
1994	66,300	1,000	3,900	9,800						81,000
1995	64,800	1,900	3,700	9,700						80,100
1996	65,500	2,900	4,000	7,900						80,300
1997	76,300	2,100	6,100	8,300	70,182	1,835	5,215	5,782	83,014	92,800
1998	66,200	1,000	7,400	7,500						82,100
1999	72,400	1,400	*7,400*	7,400						88,600
2000	81,500	700	*7,400*	5,600						95,200
2001	74,200	3,800	7,400	8,800						94,200
2002	71,800	*4,000*	*10,000*	9,200	59,522	624	11,375	13,488	85,009	95,000
2003	62,500	8,100	12,900	15,100						98,600
2004	53,500	3,900	*10,000*	14,500						81,900
2005	58,500	1,900	9,400	12,000						81,800
2006	59,300	1,800	11,800	11,900						84,800
2007	68,200	2,000	7,300	13,300	62,274	750	4,847	13,488	81,359	90,800

Appendix C: Crop Coefficient Tables

The following tables show the crop coefficients for each crop: corn, sorghum, soy, and wheat. For each crop, the "Adjusted GDD" was calculated by multiplying the GDD at each stage by X over the final harvest GDD. For wheat, $K_{c(grass)}$ was calculated by multiplying the alfalfa-based crop coefficient by 1.4, as described in the section "Crop Coefficients."

Table 13: Crop coefficient table for corn [57-58]

Crop Stage	GDD (°C-d)	Adjusted GDD (°C-d)	K_c
	0	0	0
Seeded	111	99.37944	0.25
Emerged	194	173.6902	0.35
4-leaf	286	256.0587	0.45
4-leaf	375	335.7414	0.7
6-leaf	472	422.5865	0.85
8-leaf	542	485.2582	1
10-leaf	631	564.9408	1.15
12-leaf	719	643.7281	1.2
14-leaf	853	763.6997	1.25
Tassel	875	783.3965	1.25
Silk	1011	905.1587	1.3
Blister	1139	1019.758	1.3
Milk	1264	1131.672	1.3
Dough	1389	1243.586	1.2
Dent	1528	1368.034	1
1/2 Maturity	1667	1492.482	0.9
Black Layer	1889	1691.241	0.7
Harvest	2111	1890	0

Table 14: Crop coefficient table for sorghum [57-58]

Crop Stage	GDD (°C-d)	Adjusted GDD (°C-d)	K_c
	0	0	0
Seeded	111	91.41764	0.4
Emerged	278	228.9559	0.4
3-leaf	319	262.7228	0.55
4-leaf	486	400.261	0.6
5-leaf	758	624.2754	0.7
GPD	817	672.8668	0.8
Flag	972	800.5221	0.95
Boot	1050	864.7615	1.1
Heading	1108	912.5293	1.1
Flower	1283	1056.656	1
Soft Dough	1536	1265.023	0.95
Hard Dough	1867	1537.628	0.9
Black layer	1944	1601.044	0.85
Harvest	2222	1830	0

Table 15: Crop coefficient table for soy [57-58]

Crop Stage	GDD (°C-d)	Adjusted GDD (°C-d)	K_c
	0	0	0
Seeded	92	78.25383	0.38
Emerged	222	188.8299	0.55
V-2	361	307.0612	0.6
V-3	472	401.4761	0.68
V-4	556	472.9253	0.7
V-5	694	590.306	0.8
V-6	833	708.5374	0.84
V-10	972	826.7687	0.9
V-12	1111	945	0.95
R-2	1194	1015.599	1.04
R_3	1306	1110.864	1.11
R_4	1389	1181.463	1.13
R_5	1556	1323.51	1.16
R_6	1778	1512.34	1
Phys. Maturity	1889	1606.755	0.38
Harvest	2222	1890	0

Table 16: Crop coefficient table for wheat [57, 62]

GDD (°C-d)	Adjusted GDD (°C-d)	K_c (alfalfa)	K_c (grass)
0	0	0.2	0.28
200	198	0.32	0.448
400	396	0.41	0.574
600	594	0.4	0.56
800	792	0.33	0.462
1000	990	0.36	0.504
1200	1188	0.51	0.714
1400	1386	0.7	0.98
1600	1584	0.79	1.106
1800	1782	0.82	1.148
2000	1980	0.84	1.176
2200	2178	0.85	1.19
2400	2376	0.72	1.008
2600	2574	0.45	0.63
2800	2772	0.44	0.616
3000	2970	0.32	0.448

Appendix D: Water Budget Results

The following tables show the water budget results for the target counties. The irrigation demand was calculated by modeling irrigation to maintain adequate soil moisture as detailed in "Validation of a Water Budget Model." The irrigation demand for wheat was unable to be calculated for 1985 because the growing season began in 1984; weather data for that year was not downloaded. Reno County begins in 1988 because weather data was not available prior to that year. Crop acreage was not available for 2008 or 2009, so while irrigation demand was available as a depth, the total irrigation demand in acre-feet was not able to be calculated. The total reported water use is the sum of both the surface and groundwater irrigation withdrawals for each year.

Barton County

	Irrigation Demand (mm)				Irrigation Need (acre-ft)					Total Reported Use (ac-ft)
	Corn	Sorghum	Soybeans	Wheat	Corn	Sorghum	Soybeans	Wheat	Total	
1985	216	108	120	#N/A	6859	4809	2453	#N/A	#N/A	32783
1986	228	60	108	805	9986	2387	1931	15846	33500	30952
1987	168	12	96	577	6254	578	2102	12403	23709	31729
1988	324	96	216	889	13481	5501	7884	22687	55058	30684
1989	180	60	120	949	9657	2650	4161	26642	47900	36725
1990	204	84	108	697	12732	2606	3981	17528	40941	35865
1991	372	168	252	829	27154	3924	7358	27198	72928	37908
1992	84	0	0	829	5948	0	0	15412	23733	32508
1993	84	0	48	577	6316	0	1156	6517	15543	31882
1994	264	72	132	865	22065	1445	3661	7884	38951	35398
1995	276	72	180	553	23572	1366	5453	6044	40484	36109
1996	120	36	48	877	10599	736	1174	5755	20293	36416
1997	204	48	108	661	19359	823	3863	1204	28055	36458
1998	144	0	72	721	9881	0	1787	1314	14424	36215
1999	144	60	72	649	10144	438	3022	2365	17743	36952
2000	276	48	132	649	18233	350	6938	2365	30984	37485
2001	216	108	132	733	17975	1261	5781	5343	33734	36642
2002	276	108	168	889	21557	1931	6132	6482	40114	38204
2003	396	216	276	685	27172	2759	10577	4993	50557	37805

2004	216	60	96	793	14033	810	2803	11563	32454	37320
2005	240	96	156	745	16643	701	5523	10862	37476	36675
2006	192	48	84	721	11983	718	3771	17607	37865	37171
2007	204	72	132	481	17646	657	4095	9110	35009	36181
2008	156	96	120	829	#N/A	#N/A	#N/A	#N/A	#N/A	34755
2009	204	96	108	829	#N/A	#N/A	#N/A	#N/A	#N/A	36694

Finney County

	Irrigation Demand (mm)				Irrigation Need (acre-ft)					Total Reported Use (ac-ft)
	Corn	Sorghum	Soybeans	Wheat	Corn	Sorghum	Soybeans	Wheat	Total	
1985	312	108	144	#N/A	44638	13757	4415	#N/A	#N/A	243853
1986	396	204	276	901	55500	21816	10980	214827	336803	230700
1987	276	96	192	829	47647	11457	6377	190388	284300	225248
1988	336	168	204	925	58619	15329	9977	200996	316578	257922
1989	517	312	324	1105	106218	36326	15491	241763	444219	266768
1990	288	108	192	781	60756	10761	9530	220630	335197	262018
1991	192	36	108	793	46741	3640	6622	202345	288164	264836
1992	228	108	132	985	60664	8790	6408	300241	417892	261717
1993	264	120	72	1009	66099	6438	2996	264888	378245	252120
1994	324	120	180	997	89518	6307	6175	262825	405361	253762
1995	276	120	144	697	85121	6701	3889	138952	260737	253388
1996	180	60	0	985	59127	2847	0	193576	283944	251211
1997	300	156	96	997	105662	6377	2102	207206	357052	253793
1998	228	0	72	937	75560	0	1761	187892	294680	250892
1999	156	0	0	961	55172	0	0	183950	265691	251616
2000	408	216	288	1033	136999	3469	11563	196239	386966	245744
2001	421	192	300	937	107764	4975	14672	139723	296816	251178
2002	457	276	336	1213	107847	12793	17782	184905	359252	255290
2003	372	156	228	961	90968	7800	13231	162927	305473	244745
2004	360	156	168	1081	89347	5978	7971	188811	324564	247671
2005	288	168	192	817	73580	5702	7008	164696	278874	237215
2006	348	168	192	1105	68968	5764	5606	218392	331922	236579
2007	324	108	204	889	98387	2602	4467	167885	303712	235561
2008	300	84	156	985	#N/A	#N/A	#N/A	#N/A	#N/A	234748
2009	264	84	132	697	#N/A	#N/A	#N/A	#N/A	#N/A	230633

Morton County

	Irrigation Demand (mm)				Irrigation Need (acre-ft)					Total Reported Use (ac-ft)
	Corn	Sorghum	Soybeans	Wheat	Corn	Sorghum	Soybeans	Wheat	Total	
1985	372	156	216	#N/A	5295	12811	631	#N/A	#N/A	77879
1986	228	0	84	1033	3911	0	215	85878	100004	72761
1987	276	120	132	1021	2619	11387	145	70733	94316	76005
1988	336	180	240	997	858	9066	350	75249	95026	75040
1989	168	96	108	913	2453	6272	39	53258	68913	76944
1990	312	96	192	949	6377	4730	70	76120	96997	74000
1991	276	132	180	961	7757	7708	131	75332	101031	72421
1992	252	84	156	1057	9657	3005	114	86719	110550	71769
1993	216	72	84	805	9224	1682	61	60156	79025	76513
1994	264	108	180	901	11177	3469	131	70952	95255	76996
1995	312	84	204	817	12982	2913	149	41397	63823	71381
1996	276	72	108	1129	13095	1997	237	86045	112638	75437
1997	180	60	96	793	9789	1642	140	64172	84159	73084
1998	276	108	180	949	18737	1616	131	70930	101571	76593
1999	312	120	204	697	22091	2058	149	51313	84013	77289
2000	240	36	132	865	19972	473	96	42571	70125	75183
2001	324	108	228	853	15373	1892	166	55662	81215	70633
2002	445	300	300	1057	24632	5365	219	60896	101236	60942
2003	216	120	144	877	14190	1927	105	44122	67049	61625
2004	144	36	84	961	11037	710	61	53258	72295	65508
2005	264	132	156	781	22643	2457	114	39571	71984	65179
2006	348	192	228	985	18798	3294	166	52794	83391	62927
2007	300	144	204	853	20694	1577	149	55040	86067	67615
2008	493	240	336	1153	#N/A	#N/A	#N/A	#N/A	#N/A	67604
2009	324	204	216	841	#N/A	#N/A	#N/A	#N/A	#N/A	66560

Reno County

	Irrigation Demand (mm)				Irrigation Need (acre-ft)					Total Reported Use (ac-ft)
	Corn	Sorghum	Soybeans	Wheat	Corn	Sorghum	Soybeans	Wheat	Total	
1988	288	60	144	#N/A	8619	1577	3574	#N/A	#N/A	26191
1989	144	84	132	889	3574	2453	2698	6482	16896	32268
1990	372	192	264	685	15614	5606	4914	8488	38469	28516
1991	312	168	192	721	13437	3618	4485	7621	32400	30316
1992	144	36	48	781	5466	815	946	7402	16254	31438
1993	144	0	48	541	4888	0	999	5321	12453	32567
1994	216	36	108	913	8672	749	2956	12649	27807	33744
1995	300	132	156	529	11935	2842	4156	10792	33028	31999
1996	276	96	132	817	11584	2628	3372	17274	38732	31543

1997	156	84	96	721	7003	1380	2803	13928	27904	33321
1998	228	60	132	685	11068	657	6697	11983	33783	33242
1999	36	0	0	517	1419	0	0	9228	11830	36959
2000	204	108	120	637	9977	788	5694	12303	31958	38915
2001	264	108	216	721	15320	867	12141	11037	43739	41312
2002	288	144	168	769	19236	2155	8032	24667	60100	45455
2003	300	120	216	565	24636	2715	9381	26966	70777	45176
2004	168	48	48	685	9688	841	2838	19972	37043	46757
2005	240	84	96	733	20672	1410	5010	17366	49399	48327
2006	276	144	156	841	19140	1734	9395	36790	74509	48796
2007	204	84	120	589	16604	1257	5562	29401	58694	50045
2008	156	96	108	685	#N/A	#N/A	#N/A	#N/A	#N/A	50500
2009	192	84	132	589	#N/A	#N/A	#N/A	#N/A	#N/A	51685

Stafford County

	Irrigation Demand (mm)				Irrigation Need (acre-ft)					Total Reported Use (ac-ft)
	Corn	Sorghum	Soybeans	Wheat	Corn	Sorghum	Soybeans	Wheat	Total	
1985	264	108	144	#N/A	18693	8987	7305	#N/A	#N/A	64680
1986	228	48	72	721	25214	2698	3994	35739	75161	59439
1987	240	60	108	493	26191	2825	3351	20830	59107	65400
1988	324	132	204	817	33820	4577	9381	42291	100077	71133
1989	204	132	144	925	19359	5540	7568	42492	83288	76915
1990	312	180	216	685	34276	6175	12141	43688	106978	77719
1991	276	144	216	733	34350	3889	10958	43548	103051	78445
1992	192	0	48	781	25788	0	1962	55229	92199	77325
1993	108	36	48	481	15570	618	2015	27154	50396	76489
1994	324	144	240	817	53569	2838	10249	43780	122706	79481
1995	252	132	156	505	40837	2457	5808	21154	78062	77029
1996	228	108	108	805	36032	3429	4218	19661	70378	79552
1997	132	36	36	685	20090	460	1695	28460	56338	80821
1998	240	84	132	805	40557	920	7660	30225	88179	82184
1999	72	0	48	781	10301	0	2698	30746	48606	82594
2000	276	72	156	673	44726	788	9679	22565	86398	82409
2001	252	144	228	841	40009	1314	9986	24220	83921	82758
2002	324	132	240	889	53569	867	16468	31762	114073	83227
2003	396	204	276	865	61137	2829	19240	36895	133446	82473
2004	180	48	48	733	24570	701	4362	40876	78344	82195
2005	252	72	156	769	37342	920	12241	38121	98472	81429
2006	288	144	180	913	42887	1945	13928	54922	126312	83340
2007	324	156	228	685	53924	2676	13314	56670	140649	82147
2008	228	60	120	793	#N/A	#N/A	#N/A	#N/A	#N/A	82024

2009	300	132	192	601	#N/A	#N/A	#N/A	#N/A	#N/A	82607

Stevens County

	Irrigation Demand (mm)				Irrigation Need (acre-ft)					Total Reported Use (ac-ft)
	Corn	Sorghum	Soybeans	Wheat	Corn	Sorghum	Soybeans	Wheat	Total	
1985	433	228	276	#N/A	26804	57419	3526	#N/A	#N/A	151787
1986	240	36	108	1045	14628	5413	1025	197378	242716	130638
1987	300	120	192	985	22118	11563	841	160536	216730	156569
1988	372	180	264	1009	29734	20169	3083	115520	187230	162009
1989	180	72	72	913	17081	8830	315	156778	203337	143993
1990	288	108	204	901	39733	9066	819	167526	241271	145280
1991	276	192	168	853	48151	12964	613	167920	255165	147839
1992	276	108	156	1045	55706	6189	228	186709	276479	152075
1993	276	84	144	769	61851	2514	158	139031	226171	148698
1994	312	108	204	925	72765	3824	74	153445	255676	151314
1995	288	96	180	817	72844	3118	263	130149	229305	160333
1996	228	96	132	1117	58251	4765	337	190217	281745	162409
1997	228	60	96	865	77806	2628	140	155148	261914	188018
1998	336	168	216	949	114907	6193	710	174730	329489	193580
1999	348	192	216	733	130569	6938	788	131445	299712	204403
2000	252	108	168	829	96114	1616	1226	115744	238556	207201
2001	336	156	204	901	123859	4441	2383	142233	303240	204808
2002	493	252	336	1081	164307	8094	4905	140722	353364	212553
2003	264	120	192	793	86719	5387	2803	110422	228146	207465
2004	180	108	84	949	67142	4927	1226	133556	229835	209248
2005	300	156	180	805	129641	2733	2628	111509	273900	210700
2006	384	156	252	985	126557	6662	3679	142219	310130	210739
2007	348	192	240	841	131077	6727	3504	125392	296334	215147
2008	469	252	300	1129	#N/A	#N/A	#N/A	#N/A	#N/A	216379
2009	348	192	240	877	#N/A	#N/A	#N/A	#N/A	#N/A	219468

Thomas County

	Irrigation Demand (mm)				Irrigation Need (acre-ft)					Total Reported Use (ac-ft)
	Corn	Sorghum	Soybeans	Wheat	Corn	Sorghum	Soybeans	Wheat	Total	
1985	264	120	96	#N/A	34688	13139	2908	#N/A	#N/A	84214
1986	396	132	276	889	72555	11900	8965	68061	179424	83864
1987	276	72	132	793	47043	2628	2120	56367	120176	86256
1988	288	156	180	877	44568	3473	4139	31972	93503	92003
1989	517	348	360	1057	96801	11304	6701	50875	184091	100022
1990	252	108	192	745	44332	2168	3294	61912	124117	97492
1991	216	0	96	769	45488	0	1402	35318	91342	97906

1992	204	120	72	925	37675	2234	1393	23607	72120	93061
1993	204	120	84	1009	44822	1533	1073	36054	92758	95411
1994	312	156	168	949	75498	569	2391	33908	124852	99000
1995	276	120	156	661	65276	832	2107	23366	101756	95605
1996	84	60	0	937	20081	635	0	26988	53005	99394
1997	288	84	108	973	80202	644	2404	29445	125217	100621
1998	216	0	84	889	52189	0	2269	24308	87517	98978
1999	108	0	0	913	28538	0	0	24632	59078	99885
2000	408	204	276	1009	121363	521	7454	20602	166601	102120
2001	396	132	276	913	107243	1831	7454	29292	162022	100495
2002	457	264	264	1129	119497	3854	9635	37876	189848	102220
2003	324	156	228	961	73908	4612	10735	52907	157958	102082
2004	360	156	180	1045	70295	2221	6570	55251	149262	102902
2005	288	96	192	721	61492	666	6587	31534	111421	102230
2006	348	192	180	1129	75319	1261	7752	48992	148138	101074
2007	300	120	168	889	74675	876	4476	43106	136814	99311
2008	276	84	132	1057	#N/A	#N/A	#N/A	#N/A	#N/A	98241
2009	204	72	108	625	#N/A	#N/A	#N/A	#N/A	#N/A	98632

Appendix E – Average Water Surface Elevation

The following table shows the average water surface elevation for the target counties from 1985 through 2010. This data was calculated using the wells located in the WIZARD database; the WWC5 database was not used for this set. After the table of water surface elevations is a list of the major functions used in ArcMap and their syntax.

COUNTY	YEAR	MIN	MAX	RANGE	MEAN	STD
Barton	1985	1722	1941.04	219.035	1825.45	48.9978
Barton	1986	1724.55	1941.45	216.907	1825.81	49.0446
Barton	1987	1719.4	1941.35	221.953	1825.9	49.4728
Barton	1988	1724.43	1940.75	216.326	1827.68	49.6642
Barton	1989	1717.93	1940.49	222.555	1827.02	50.693
Barton	1990	1720.36	1940.86	220.498	1827.46	50.093
Barton	1991	1726.12	1939.98	213.858	1827.3	48.9202
Barton	1992	1724.96	1935.69	210.727	1826.2	48.8102
Barton	1993	1727.55	1938.67	211.121	1830.87	47.2852
Barton	1994	1729.77	1941.84	212.064	1834.44	48.3467
Barton	1995	1726.29	1940.45	214.159	1831.88	48.2146
Barton	1996	1728.58	1942.1	213.521	1833.2	47.7206
Barton	1997	1729.3	1941.31	212.018	1836.66	44.6793
Barton	1998	1730.41	1941.39	210.986	1836.91	45.1243
Barton	1999	1729.29	1939.96	210.667	1837.21	43.9837
Barton	2000	1731.51	1932.79	201.274	1837.22	44.9079
Barton	2001	1730.58	1932.05	201.472	1836.58	44.7364
Barton	2002	1730.34	1935.03	204.685	1836.78	45.332
Barton	2003	1729.52	1933.18	203.664	1835.39	45.3993
Barton	2004	1729.18	1928.71	199.524	1834.23	44.8318
Barton	2005	1729.28	1932.23	202.943	1834.29	44.9066
Barton	2006	1729.84	1927.75	197.908	1831.69	44.9366
Barton	2007	1728.92	1932.26	203.342	1832.74	45.2046
Barton	2008	1731.39	1935.15	203.764	1835.16	46.6323
Barton	2009	1732.56	1935.98	203.427	1836.67	47.4521
Barton	2010	1732.56	1936.29	203.725	1835.66	46.8726
Finney	1985	2308.19	2908.17	599.982	2785.36	56.1479
Finney	1986	2306.19	2908.05	601.869	2784.64	55.5402
Finney	1987	2303.9	2916.67	612.769	2786.02	56.5594
Finney	1988	2303.84	2917.79	613.95	2785.19	58.3788

COUNTY	YEAR	MIN	MAX	RANGE	MEAN	STD
Finney	1989	2300.62	2916.88	616.264	2783.25	58.8202
Finney	1990	2302.74	2916.97	614.229	2781.66	58.9307
Finney	1991	2482.06	2916.31	434.251	2779.44	54.014
Finney	1992	2300.12	2915.1	614.979	2778.8	59.607
Finney	1993	2305.03	2915.57	610.54	2776.82	58.8125
Finney	1994	2310.92	2917.08	606.16	2777.35	59.1035
Finney	1995	2309.43	2915.4	605.97	2775.94	59.5624
Finney	1996	2306	2912.65	606.641	2772.13	58.1352
Finney	1997	2307.43	2915.51	608.081	2775.23	59.1838
Finney	1998	2309.08	2923.05	613.97	2776.19	60.1178
Finney	1999	2307.86	2923.99	616.135	2774.93	60.8683
Finney	2000	2307.93	2922.49	614.561	2773.42	60.7874
Finney	2001	2306.1	2917.41	611.308	2771.05	60.6567
Finney	2002	2303.91	2913.55	609.64	2770.64	61.3139
Finney	2003	2301.04	2918.23	617.186	2765.87	61.0551
Finney	2004	2301.7	2891.47	589.767	2760.23	59.2111
Finney	2005	2302.15	2892.36	590.212	2758.98	59.8631
Finney	2006	2301.73	2892.96	591.229	2756.66	60.2217
Finney	2007	2302.62	2901.23	598.61	2753.7	61.033
Finney	2008	2300.16	2905.1	604.941	2752.14	61.8609
Finney	2009	2451.64	2904.19	452.552	2750.01	59.2686
Finney	2010	2293.55	2906.76	613.211	2746.36	63.6516
Morton	1985	3021.48	3559.64	538.157	3312.02	135.713
Morton	1986	3022.01	3551.64	529.627	3311.28	136.579
Morton	1987	3019.26	3555.44	536.187	3308.9	138.676
Morton	1988	3012.23	3556.41	544.174	3309.45	140.396
Morton	1989	3009.43	3554.64	545.209	3304.33	137.09
Morton	1990	3006.78	3554.07	547.286	3308.15	138.55
Morton	1991	2998.69	3545.04	546.353	3308.14	134.127
Morton	1992	3018.23	3544.42	526.187	3306.8	135.294
Morton	1993	3006.02	3545.25	539.235	3300.3	131.801
Morton	1994	3002.77	3540.28	537.515	3305.77	137.215
Morton	1995	3012.25	3541.45	529.202	3305.35	134.973
Morton	1996	3002.47	3541.03	538.564	3293.94	131.449
Morton	1997	2997.73	3539.58	541.849	3294.32	129.182
Morton	1998	3000	3541.05	541.044	3294.55	129.841
Morton	1999	2990.54	3542.04	551.5	3295.04	128.878
Morton	2000	2989.24	3542.96	553.723	3295.38	132.51
Morton	2001	2988.25	3540.87	552.625	3291.44	133.436
Morton	2002	2987.25	3544.27	557.024	3291.4	135.089
Morton	2003	2985.64	3542.4	556.765	3289.12	134.451

COUNTY	YEAR	MIN	MAX	RANGE	MEAN	STD
Morton	2004	2981.27	3544.68	563.413	3289.11	134.406
Morton	2005	2981.24	3544.99	563.754	3291.34	135.136
Morton	2006	2981.52	3544.73	563.213	3293.98	136.85
Morton	2007	2978.87	3545.17	566.293	3288.23	125.593
Morton	2008	2976.39	3545.41	569.025	3293.16	136.777
Morton	2009	2971.18	3545.29	574.104	3292.31	137.342
Morton	2010	2970.34	3545.06	574.715	3291.33	136.92
Reno	1985	1404.41	1774.82	370.416	1606.89	94.3659
Reno	1986	1409.33	1776.02	366.686	1608.3	93.4529
Reno	1987	1407.83	1776.18	368.348	1608.9	93.1045
Reno	1988	1412.77	1779.43	366.662	1608.19	94.6323
Reno	1989	1407.13	1775.11	367.977	1604.85	95.3719
Reno	1990	1407.98	1776.26	368.277	1606.05	95.3719
Reno	1991	1401.09	1775.62	374.529	1605.08	94.8907
Reno	1992	1396.73	1774.05	377.321	1602.31	94.6327
Reno	1993	1406.69	1774.93	368.248	1603.67	94.4941
Reno	1994	1395.46	1779.63	384.17	1604.45	97.1827
Reno	1995	1406.6	1774.99	368.394	1603.99	94.7469
Reno	1996	1408.35	1775.04	366.691	1604.97	94.223
Reno	1997	1408.17	1775.16	366.984	1605.46	93.6772
Reno	1998	1415.63	1776.39	360.758	1606.41	93.4038
Reno	1999	1416.18	1776.2	360.025	1606.52	93.3108
Reno	2000	1419.38	1775.39	356.007	1606.18	93.2596
Reno	2001	1415.69	1774.36	358.663	1605.51	93.335
Reno	2002	1410.5	1774.6	364.094	1604.83	93.7222
Reno	2003	1407.17	1772.86	365.693	1603.44	95.1123
Reno	2004	1406.81	1772.97	366.165	1604.17	93.7345
Reno	2005	1411.99	1773.77	361.78	1605.21	93.8948
Reno	2006	1410.62	1775.93	365.314	1605.08	94.3876
Reno	2007	1407.22	1772.36	365.139	1603.13	94.1621
Reno	2008	1410.29	1776.1	365.816	1605.88	94.2234
Reno	2009	1415.6	1777.2	361.591	1606.65	94.5752
Reno	2010	1413.6	1780.91	367.309	1607.43	95.1924
Stafford	1985	1720.24	2032.05	311.811	1870.14	71.314
Stafford	1986	1725.28	2032.62	307.34	1871.98	70.9506
Stafford	1987	1723.01	2032.27	309.264	1871.95	71.2648
Stafford	1988	1739.01	2036.22	297.212	1876.24	69.6775
Stafford	1989	1722.39	2031.69	309.304	1872.1	70.2472
Stafford	1990	1722.33	2031.28	308.955	1871.92	70.5668
Stafford	1991	1723.06	2029.83	306.767	1870.25	70.4088
Stafford	1992	1721.87	2029	307.125	1868.32	70.6831

COUNTY	YEAR	MIN	MAX	RANGE	MEAN	STD
Stafford	1993	1722.39	2035.63	313.235	1869.3	70.3081
Stafford	1994	1726.35	2040.34	313.985	1874.65	70.1578
Stafford	1995	1722.94	2036.16	313.226	1871.67	70.3227
Stafford	1996	1723.04	2039.22	316.178	1871.61	70.4827
Stafford	1997	1723.85	2040.92	317.068	1872.43	70.8818
Stafford	1998	1723.54	2044.26	320.721	1873.11	71.1632
Stafford	1999	1723.62	2039.85	316.232	1873.12	70.9293
Stafford	2000	1723.91	2041.14	317.236	1873.11	71.0804
Stafford	2001	1722.99	2044.09	321.106	1872.5	70.7092
Stafford	2002	1722.74	2033.35	310.609	1872.06	70.3234
Stafford	2003	1722.08	2030.78	308.697	1870.42	69.8372
Stafford	2004	1721.85	2028.72	306.877	1869.09	69.3749
Stafford	2005	1721.99	2029.13	307.132	1869.32	69.3998
Stafford	2006	1722.51	2029.6	307.092	1870.25	69.132
Stafford	2007	1721.6	2026.9	305.3	1868.7	69.2947
Stafford	2008	1723.91	2032.35	308.446	1873.21	70.0282
Stafford	2009	1725.05	2033.87	308.821	1874.39	69.8774
Stafford	2010	1724.89	2034.39	309.497	1875.48	69.993
Stevens	1985	2707.2	3153.32	446.118	2952.7	98.7381
Stevens	1986	2703.05	3152.28	449.232	2950.64	100.037
Stevens	1987	2702.53	3151.4	448.868	2948.67	102.974
Stevens	1988	2701.15	3151.11	449.955	2949.2	99.7077
Stevens	1989	2712.97	3148.78	435.813	2945.51	96.1198
Stevens	1990	2691.61	3149.06	457.458	2943.05	99.7466
Stevens	1991	2694.02	3148.79	454.776	2941.79	101.677
Stevens	1992	2714.1	3149.18	435.083	2940.87	101.676
Stevens	1993	2710.59	3146.87	436.271	2939.88	99.5996
Stevens	1994	2710.33	3147.09	436.766	2939.61	99.9345
Stevens	1995	2703.29	3145.78	442.484	2937.14	104.499
Stevens	1996	2700.94	3144.02	443.079	2933.95	99.9524
Stevens	1997	2700.58	3143.43	442.847	2930.11	103.06
Stevens	1998	2702.33	3143.46	441.133	2925.06	102.895
Stevens	1999	2700.42	3142.35	441.929	2920.12	104.222
Stevens	2000	2698.57	3141.48	442.916	2916.03	102.207
Stevens	2001	2696.7	3140.68	443.976	2910.73	101.909
Stevens	2002	2702.91	3140.51	437.6	2911.92	101.331
Stevens	2003	2691.49	3140.35	448.861	2904.35	107.143
Stevens	2004	2690.31	3139.05	448.742	2901.54	107.967
Stevens	2005	2692.87	3138.05	445.174	2902.82	105.603
Stevens	2006	2680.61	3136.88	456.273	2898.56	107.618
Stevens	2007	2680.04	3135.4	455.361	2895.52	106.837

COUNTY	YEAR	MIN	MAX	RANGE	MEAN	STD
Stevens	2008	2678.01	3133.93	455.922	2888.98	105.977
Stevens	2009	2675.28	3133.05	457.773	2883.94	106.842
Stevens	2010	2673.11	3132.9	459.791	2880.66	107.729
Thomas	1985	2810.5	3318.86	508.367	3054.41	125.239
Thomas	1986	2809.93	3328.86	518.925	3054.96	126.358
Thomas	1987	2805.65	3328.08	522.425	3054.36	126.331
Thomas	1988	2805.85	3328.16	522.311	3054.02	126.937
Thomas	1989	2809.81	3329.58	519.773	3051.74	124.206
Thomas	1990	2806.39	3325.39	518.997	3051.1	126.09
Thomas	1991	2804.17	3318.16	513.991	3050.24	126.939
Thomas	1992	2793.08	3316.32	523.247	3048.49	125.129
Thomas	1993	2790.39	3332.4	542.005	3045.79	127.027
Thomas	1994	2817.79	3331	513.207	3051.46	126.563
Thomas	1995	2816.9	3330.95	514.053	3051.31	127.682
Thomas	1996	2815.54	3331.46	515.924	3051.06	128.47
Thomas	1997	2821.22	3326.09	504.869	3051.9	124.718
Thomas	1998	2809.66	3326.01	516.352	3048.31	127.15
Thomas	1999	2810.51	3326.21	515.697	3048.58	126.522
Thomas	2000	2811.12	3327.18	516.056	3047.96	127.16
Thomas	2001	2807.07	3325.74	518.672	3046.79	127.283
Thomas	2002	2806.96	3325.82	518.861	3047.33	129.028
Thomas	2003	2807.92	3324.5	516.58	3046.14	129.225
Thomas	2004	2805.22	3322.69	517.471	3045.27	129.027
Thomas	2005	2801.54	3324.74	523.198	3043.55	128.019
Thomas	2006	2799.97	3324.16	524.196	3043	128.546
Thomas	2007	2803.28	3365.79	562.514	3039.25	133.174
Thomas	2008	2801.55	3322.62	521.066	3041.23	128.2
Thomas	2009	2795.31	3322.19	526.887	3040.52	128.521
Thomas	2010	2794.92	3322.65	527.736	3040.81	128.285

Select_analysis <in_features> <out_feature_class> {where_clause}
AddField <in_table> <field_name> <field_type>
CalculateField <in_table> <field> <expression>
DeleteField <in_table> <drop_field; drop_field...>
Merge_management <inputs; inputs...> <output>
Project_management <in_dataset> <out_dataset> <out_coor_system>
Idw_sa <in_point_features> <z_field> <out_raster> {cell_size}
ZonalStatisticsAsTable_sa <in_zone_data> <zone_field> <in_value_raster> <out_table>
AddField <in_table> <field_name> <field_type>
TableToDBASE <Input_Table;Input_Table...> <Output_Folder>